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ASTRONOMY.—*Great astronomical treatises of the past.*[1]

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INTRODUCTION

Through the ages, the torch of learning has been handed on largely by means of tangible records and documents—in ancient times by inscriptions and written manuscripts, in more recent times by printed books. In the development of the sciences this transmission of knowledge from generation to generation and from one civilization to another is as vital a factor as the observation and the creative thought by which knowledge is first brought into existence, because without the benefit of accumulated information, experience, and thought from the past, no natural science could be brought to a highly advanced state.

The progressive evolution of astronomy from its emergence in remote antiquity to its present highly developed form, as recorded in the extant writings from successive periods during the past 3,000 years or more, is one of its principal sources of general interest; a knowledge of modern astronomy is immeasurably enriched, and its fascination and romance are greatly enhanced, by a familiarity with the circumstances of its beginnings and early development, the methods by which astronomical observations and calculations have been made and results established throughout past times, and the succession of concepts to which the steady accumulation of observed facts gave rise, until finally the subject attained its present form. This historical development is also of direct technical interest; a familiarity with the provenience and evolution of astronomical ideas and practices—their adumbration, filiation, and development—and with the reasoning by which principles and theories have been successively formulated through the centuries is of inestimable didactic value in contributing to a clear and appreciative comprehension and a convincing understanding of the now established concepts, accepted technical practices, and prevailing theories to which the course of thought during the past has progressively led. Many astronomical ideas and procedures, although they have evolved from origins in simple concepts naturally suggested by observation and have developed by a succession of steps each natural in itself, are in their present form so remote from their beginnings that they may seem far from natural; the categorical presentation of modern refined concepts and established results in systematic logical form, with the description of the elaborate instrumental equipment, complex observational procedures, and intricate mathematical calculations on which they now are based, is greatly illuminated by an indication of the path actually followed historically in the progressive construction of this system with the former methods and means available at successive times during its development. Historical knowledge and perspective *with critical insight* will also prevent the attitude of scepticism sometimes engendered by the revisions of thought continually involved in the progress of the sciences; it will lead to a more adequate realization of the intrinsic merit of the ancient learning, and to a recognition of the importance of this learning both as a basic element in our own knowledge and as an indispensable foundation for the derivation

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of many modern results; and it will materially aid toward the desirable end of integrating scientific knowledge with the rest of human culture.

The historian himself, in the difficult task of constructing as complete and accurate an account as possible of the development of astronomy, must critically study *all* the surviving earlier astronomical records and documents—the sole original source of information—from every land. In all times (including the present), however, among the total multitude of existing books there have always been a limited few that stand out from others in their field and with the passage of time survive as monuments, either marking a particularly fundamental advance through the accounts of important original investigations they contain or else being of permanent value as outstanding presentations of the state of knowledge of their subject at the time; and the greater among these writings are worthy of being treasured and read by all students and lovers of astronomy as well as by historians. These great scientific works are as precious a heritage as other imperishable literature from the past; they offer the reader rich rewards in pleasure and satisfaction and are a valuable auxiliary to the general histories of astronomy. No more effective or inspiring method is available for extending the usual textbook information about the outstanding developments and advances during the past than to study the actual original writings wherein those who were the principal contributors give their own expositions of their work and describe the procedures by which they arrived at their results; no textbook account of any of these works can take the place of an actual examination of the original.

The purpose of the present paper is to indicate the more noteworthy writings that have been of the greatest significance in either determining or recording the historical evolution of astronomy, from ancient to modern times; and in the case of each, to discuss briefly its part in the development of astronomical thought, and to provide bibliographical references to printed editions now available to the general reader.

Astronomy may be broadly divided into (1) spherical and practical astronomy—the observation, exact description, and systematic discussion of the apparent positions and motions of the heavenly bodies on the celestial sphere; (2) theoretical astronomy —the construction of systematic theories of the actual arrangement and real motions of the celestial bodies in space that will account for the observed phenomena and from which these phenomena may be predicted by mathematical calculation; and (3) descriptive astronomy and astrophysics —the observation and physical interpretation of the characteristic features and intrinsic natures of the individual celestial bodies. During the pretelescopic period, from antiquity to the early seventeenth century, astronomy was practically confined to the first and second of these subdivisions, i.e., to what may be called "fundamental astronomy"; moreover, this part of astronomy, though now overshadowed by astrophysics (the rise of which began shortly after the middle of the nineteenth century), forms the essential foundation and framework of the entire science. In this paper we therefore confine ourselves to fundamental astronomy, and shall limit the discussion to the period closing with Laplace (d. 1827) and Bessel (d. 1846).

For readers whose interest is primarily in astronomy itself, rather than in history as such, the principal criterion for appraising the relative importance of early writings will be their comparative significance in having influenced the developments of thought that actually led to the eventual establishment of our own learning. Contrary to the impression likely to be conveyed by some modern writers, the astronomical ideas that now prevail in our civilization are not simply the chronologically latest of a discontinuous succession of mutually independent systems of thought, each a complete revolution over its predecessors, and all (with the exception of the most recent!) of little merit. Instead, fundamental astronomy as it now exists is the outcome of an essentially unbroken development extending from remote antiquity to modern times, throughout which the ac-

cumulated learning from the past conserved and transmitted down the centuries by successive civilizations, was explicitly the basis for progressive extensions and attendant successive *revisions in particulars* that gradually led to the now established system. Modern astronomy has developed out of the ancient learning; and in it old and new ideas are combined in a design woven in many lands through many ages. A study of the more important original writings from successive periods will lead to a realization of this essential *continuity of the development*, and to an appreciation of the enduring importance of the earlier learning for the later achievements. Necessarily, to have been of significance in this development, knowledge that originated at any particular time and place must, through some channel, have become synthesized with the astronomical thought of the civilizations by way of which our own civilization has received its culture; from the scientific astronomical point of view, any knowledge that developed in isolation from the particular stream of thought through which learning historically became established in our own civilization is of only limited interest, although it may be of the utmost significance and importance from other points of view.

Hence a generalized sketch of the historical development of astronomy within a framework of social and political history is an essential background for a discussion of the astronomical writings of the past and their significance.[2]

DEVELOPMENT OF ASTRONOMY IN RELATION TO POLITICAL HISTORY

Modern science is essentially a development of Western learning, but it has been founded upon the heritage from the ancient Orient, where the earliest civilizations appeared. Of the three principal cultural groups in the world, broadly speaking—the Chinese, the Hindu, and our own—all three are of Eastern origin; but the first two remained exclusively Eastern, while the third has developed from a blend of Eastern and Western elements. Civilization and culture in Europe, during both ancient and medieval times, originated by diffusion westward from the nearer Orient, by way of the Mediterranean regions.

The historic period—i.e., the era of contemporary written records of the history and culture of mankind—first opens about 3100 B.C. in Egypt along the Nile River, and somewhat earlier in Sumer along the lower Tigris and Euphrates; but archeological explorations have shown that in these regions and also in some other parts of the great crescent-shaped area that stretches northward along the eastern shore of the Mediterranean and eastward and southward down the Tigris and Euphrates to the Persian Gulf, as well as in parts of Asia Minor, the development of civilization had been in progress over a period which in some localities probably extends back to 4500 B.C. or earlier. Through trade and commerce, migration and colonization, warfare and conquest, the ancient peoples of western Asia and the eastern Mediterranean regions were in continual contact with one another; and, under cultural influences from Egypt and Sumer, Oriental civilization steadily spread and developed among the other early nations that became established in western Asia,[3] while one great empire after another rose to political supremacy over the region.

[2] In preparing the following historical section, the author has relied principally upon: J. H. BREASTED, *The conquest of civilization*, new ed. (New York), 1938. J. H. BREASTED, *Ancient times*, 2d ed. (Boston), 1935. *Cf.* V. G. CHILDE, *The Orient and Europe*, Rept. Brit. Assoc. Adv. Sci. for 1938, pp. 181–196; and E. A. SPEISER, *Ancient Mesopotamia and the beginnings of science*, Univ. Pennsylvania Bicentennial Conference: Studies in the History of Science, pp. 1–11 (Philadelphia), 1941.

[3] Particularly the Phoenicians along the Mediterranean coast in north Syria and the Canaanites in Palestine, among both of whom a flourishing civilization had developed by the twentieth century B.C.; the Hittites in Anatolia (Asia Minor), from remote times until the great empire they built up in Asia Minor, Syria, and eastward beyond the Euphrates, finally collapsed under barbarian invasions about 1200 B.C.; and, in somewhat later times, the Syrians (Arameans) who had developed a flourishing civilization (especially at Damascus) by 1200 B.C., and the Hebrews, who began to displace the Canaanites after 1400 B.C. and developed a notable culture in Judea after the ninth or eighth century B.C.

Sumer had come under the control of Akkad, just to the north, by the twenty-sixth century B.C., when Sargon built up a powerful nation in western Asia that extended from Elam at the head of the Persian Gulf, far up the Tigris and Euphrates to the west and north, penetrating to the Mediterranean and probably into eastern Asia Minor; after about 2300 B.C., the whole lower Tigris-Euphrates region (Plain of Shinar) was a unified nation under both Sumer and Akkad with a great civilization centered at the city of Ur, but it declined after 2200 B.C. before the attacks of invaders, Sumer and Ur falling to the Elamites. Later, however, Amorites from Syria, invading Akkad, seized the town of Babylon, and before 1900 B.C., under Hammurabi, had become supreme over the entire region of Sumer and Akkad, which henceforth was known as Babylonia. This early Babylonian civilization had been completely destroyed by about 1750 B.C. through a plundering invasion by Hittites, and subsequent permanent occupation by Kassites from the east; and cultural progress ceased. Still farther north along the Tigris, however, was a civilization drawn largely from Sumeria that had for many centuries been developing at Assur. About 1300 B.C. Assur commenced to extend her power, first over the Tigris-Euphrates region and then over other areas, until finally, by the capture of Damascus in 732 B.C. and the conquest of Egypt in 674 B.C.,[4] the Assyrian Empire had come to include the whole of western Asia and the Nile Valley. Under the Assyrians the ancient learning was revived; the time of Assurbanipal (d. 626 B.C.) was the golden age of Assyrian art and learning in which astronomy held an important place, though it was in part only a reflection of more ancient Assyrian and Babylonian culture.

[4] Egypt, except for a brief period of domination by the Hyksos from Syria in the seventeenth century B.C., had until this time been independent, and in fact during the sixteenth and fifteenth centuries B.C. had extended her own power until the eastern shore of the Mediterranean and some of the territory over to the northern Euphrates had been brought under her rule; after 1400 B.C., however, under invasions (especially by the Hittites) and revolts, the Egyptian Empire in Asia began to decline and finally collapsed about 1150 B.C.

Meanwhile, the desert tribes of the Chaldeans had been establishing themselves at the head of the Persian Gulf and gradually mastering Babylonia, while the Medes were advancing from the northeastern mountains; under their combined assault, Nineveh was destroyed in 612 B.C., and the Assyrian Empire fell. The Medes established a strong Iranian kingdom in the mountains east of the Tigris, extending from the Persian Gulf to the Black Sea, while the Chaldeans ruled the whole of the Tigris and Euphrates Valleys and the eastern Mediterranean shores, with their capital at Babylon, reviving the early Babylonian civilization, which had perished centuries before, and attaining a much higher level (particularly in astronomy); but 60 years after the fall of Nineveh the Iranian tribes known as the Persians, who had long been settled in the mountains of Elam at the head of the Persian Gulf, conquered the Medes, brought the Chaldean Empire to an end by the capture of Babylon in 538 B.C., and by 525 B.C. had extended the Persian Empire over Egypt, western Asia and Asia Minor, and eastward almost to India. Iranian culture and learning, dawning about the sixth century B.C. at the time of Zoroaster, advanced to high levels under the influence of the conquered civilizations; much of the most important Chaldean astronomical work was done under Persian rule.

Persia was the last of the great Oriental powers of antiquity; political and cultural supremacy were now to pass temporarily to the West, where another civilization had already begun to arise.

As early as 2000 B.C., under Egyptian and Hittite influence, a high level of civilization had become established on the island of Crete and was beginning to spread to the adjacent coast of the Aegean Peninsula to the northwest, where an especially notable development took place at Mycenae after 1600; but a succession of barbarian invasions of the Aegean region by tribes from the north, migrating southward west of the Black Sea, which began before 2000 B.C., had almost destroyed this early Aegean civilization by 1200 B.C. or before, and led to many migrations and disturbances through-

out the eastern Mediterranean regions. Between 1300 and 1000 B.C., these invading tribes—the ancestors of the later Greeks—became established throughout the Aegean region, including the coast of Asia Minor, commingling to some extent with the earlier Aegean peoples; and among them, from the surviving remnants of the Cretan civilization and under continued Oriental influences, civilization and culture began slowly to develop. After the sixth century B.C., Greek civilization and learning made remarkable progress, and during the next few centuries the Greeks achieved the highest civilization and greatest culture ever attained in the ancient world.

Greece did not come under Assyrian or Persian rule, although Greek colonies in Asia Minor were at times conquered; but in the fourth century B.C. the Macedonians, north of the Greek Peninsula, began a series of conquests that by 338 B.C. had made them masters of all Greece, by 333 had overthrown the Persian Empire, and by 323 had built up the vast empire of Alexander the Great, which included Greece, Egypt, Asia Minor, and western Asia over into India. The Macedonian rulers had been strongly influenced by the Greek culture; the conquests of Alexander carried Greek civilization throughout the ancient world and into the very heart of Asia, and at the same time materially enlarged Greek learning. After Alexander's death his empire became divided under different Macedonian leaders: The kingdom of the Ptolemies was established in Egypt; the Seleucids ruled over western Asia, but the Seleucid Empire soon began to disintegrate—in particular, Bactria (adjacent to India) became independent in 250 B.C.; and Parthia (north of Persia) not only became a separate country in 249 B.C., ruled by the Arsacid dynasty, but during the second century B.C. built up an empire of its own that included Babylonia. From the many centers of influence founded by the Macedonians, the Greek culture continued during the next three centuries to spread and become widely established, particularly in Egypt, western Asia, and India. Alexandria, founded in 332 B.C., became the leading intellectual center of the world. At the same time, the Babylonians continued their own developments, especially in astronomy, through the Seleucid and Arsacid periods, and contributed materially to Greek learning.

Meanwhile, the vast power of Rome had been slowly rising in the West: The western Mediterranean lands had long remained in a state of barbarism, little influenced by the Oriental civilizations. It was in Italy and Sicily that the West first began to be influenced by the eastern Mediterranean culture, largely through westward migrations (especially of the Etruscans) beginning in the twelfth century B.C. and through contact with Greek and Phoenician colonies founded in that region while Rome was still a rude barbarian settlement. The Latin (Italic) tribes then occupying central Italy, after having been subject to the Etruscans from the eighth century B.C. until about 500 B.C., had become securely established under the leadership of Rome by about 400 B.C.; and the city of Rome then began to expand her power. By 275 B.C. Rome controlled Italy north of the Po; she then began the development of an empire that successively took in all of Italy, the Phoenician colony of Carthage on the African coast, Macedonia, the eastern empires that had been formed from Alexander's empire, Greece, Egypt, and eventually the still barbaric peoples of western Europe, reaching its greatest extent about 100 A.D. The Romans themselves added little to Greek learning; but as Roman civilization developed during the growth of the empire, it continually became more and more influenced by the Greeks (though its foundation was Etruscan), establishing the Greek culture and language still more firmly throughout the civilized world.

Barbarian invasions, which began about the third century A.D., combined with internal strife and decline, and the rise of a New Persia in the Tigris-Euphrates region (under the Sassanians), led to a division of the Roman Empire in the fourth century into Eastern and Western Empires, and finally to its collapse and breakup. In the West, the ancient world came to a final end in 476 A.D., the Western Roman Empire

having been completely replaced by barbarian kingdoms; the ancient civilization and learning almost disappeared in the West, and the Dark Ages settled over Europe. In the East, classical learning steadily declined; and a rapid rise of the Moslem Arabs in the early seventh century destroyed the remaining Eastern Roman Empire (Byzantine Empire) except for a small fragment in Asia Minor and the Balkan peninsula ruled by the successors of the Roman Emperors at Constantinople, where the ancient civilization survived until the Turkish conquest in 1453.

By 750 A.D. the Moslem Empire included Arabia, western Asia (over to India), Egypt and northern Africa, and Spain; the capital was at Baghdad. After the middle of the eighth century the Moslems actively cultivated the ancient learning that came into their possession: First, from their contacts with the peoples of the Tigris-Euphrates region and, after the conquest of Persia, with the scholars of India, they obtained Babylonian and Hindu knowledge and also the Greek learning that had been transmitted to those regions; later, they came into contact with the original Greek writings. The culture of Islam—a fusion of Arabic with Persian and Greco-Persian elements—soon became supreme throughout the learned world, and Arabic the principal literary language. The Moslem supremacy in Asia declined after the tenth century, but continued in Spain (among the Moors) until the capture of Cordova and Seville by the Spaniards in the thirteenth century, and survived still longer in Egypt. The rise of Mongol power in Asia during the thirteenth century, with the capture of Baghdad in 1258, destroyed the Eastern Caliphate. Under the Mongols, Persia became for a time a leading center of learning, but during the fifteenth century intellectual progress came to an end in the East.

Meanwhile, the cultivation of classical learning, gathered from Persia, Mesopotamia, Syria, Egypt, and the Byzantine Empire, and concentrated with knowledge from India, by Moslem scholars of many different nationalities, had carried the legacy of the ancients westward along both the northern and southern shores of the Mediterranean as far as Spain and Morocco. During the eleventh century, the Arabic learning had commenced to spread slowly from Spain into other parts of western Europe, but this diffusion did not reach significant proportions until about the thirteenth century. Finally, during the fifteenth and sixteenth centuries, the Renaissance in western Europe opened the modern era, first in Italy and then successively in other countries.

During the course of the long succession of historical events sketched above, the cultivation of astronomy among the nations that were involved resulted in the eventual establishment of astronomical learning in its present form in our own civilization.[5]

The astronomical knowledge that developed among the ancient Oriental nations of the pre-Hellenic period as a result of centuries of continued astronomical observation—principally in Egypt and Babylonia, where the cloudless skies and clear atmosphere were especially favorable for the observation of celestial phenomena—constituted the beginning from which modern astronomy has evolved. Historical records from ancient Egypt give evidence of astronomical observation extending back into the early third millennium, although no actual records of systematic observations from any period are known, nor are any specific Egyptian observations used in extant writings from later times. From Babylonia, written records of observations of the planet Venus made nearly 4,000 years ago are still extant; but not until after the eighth century B.C. did the Babylonian astronomical observations become sufficiently systematic and precise to lead to a very exact knowledge of celestial phenomena. The earliest observations were necessarily simple, and more or less rough: All ancient peoples grouped the brighter

[5] The development of astronomy is included in the general summaries of scientific and cultural progress among different nations given in the various introductory sections and chapters of GEORGE SARTON, *Introduction to the history of science*, Carnegie Inst. Washington Publ. No. 376; volumes 1 (1927) and 2 (1931) cover the period from antiquity through the thirteenth century.

stars into constellations; introduced the zodiac in one form or another, as a means of following the apparent motions of the sun, the moon, and the five planets visible to the unaided eye; and based calendars, and methods of measuring time, on celestial phenomena. Particular attention was always given to eclipses, heliacal risings and settings of the planets and bright stars, conjunctions, and other similar occurrences. From centuries of observation, the characteristics of the apparent motions of the sun, moon, and planets among the fixed stars became accurately enough known, especially in Babylonia, for empirical methods of predicting celestial phenomena to be constructed. In general, astronomy was cultivated largely for religious and astrological purposes.

Babylonian astronomy was gradually developed during the 3,000 years or more preceding the Christian Era, by the various peoples who occupied the Tigris-Euphrates region from Sumerian to Roman times. It remained primitive until during the late Assyrian period, when a continuous series of carefully recorded systematic astronomical observations began with the reign of Nabonassar in 747 B.C. and extended over several centuries. From the long records of observations, the later Babylonians obtained an accurate knowledge of the periods and principal inequalities of the apparent motions of the celestial bodies, and constructed elaborate methods for mathematically representing these motions and calculating remarkably exact ephemerides of the positions and principal phenomena of the sun, moon, and planets, including the prediction of eclipses. Babylonian astronomy reached its most advanced stage during the third and second centuries B.C. at the period when Greek astronomy was rapidly developing; and the Greeks, especially Hipparchus, used many of the Babylonian results.

Egyptian astronomy never approached the level attained by Assyro-Babylonian learning, nor apparently was it ever greatly influenced by the Greek and Babylonian knowledge, and it can not compare in importance with the Babylonian as a foundation for Greek astronomy. The later Egyptians developed methods for roughly calculating the apparent motions of the moon and the planets, but they never advanced beyond simple approximate procedures in which no account was taken of the details of the inequalities.

The Chaldean astronomy was the earliest scientific system of astronomical knowledge; but apparently it was entirely empirical, and dominated by religious and astrological motives. There is no certain evidence that either the Egyptians or the Babylonians constructed any explanatory theories, other than primitive mythological cosmologies, to account for the phenomena they observed or for the empirical rules they developed. Upon the basis of the accumulated Oriental knowledge, however, particularly that of the Chaldeans, the ancient Greeks initiated the development of astronomy as a logical science, by introducing natural physical law and abstract rational thought in place of mythology and mysticism, formulating general principles in place of particular statements, and constructing systematic physical and mathematical theories of the arrangement and motions of the heavenly bodies in space for the explanation and calculation of celestial phenomena in place of a collection of empirical rules. Ancient astronomical science was essentially and almost wholly a creation by the Greeks; but the Orient provided the initial stimulus to the constructive intellectual genius of the Greeks, and supplied an indispensable foundation of observational data and empirical results from 30 centuries of activity. It was among the Ionians, in closest contact with the Orient, that Greek philosophy and science first began to develop.

The astronomical and mathematical knowledge of their Oriental predecessors and contemporaries began to be introduced among the Greeks about the seventh century B.C., and Greek philosophy appeared in the sixth century with Thales and the Pythagoreans, although scientific astronomy as distinguished from philosophical speculation did not begin until the early fourth century B.C. While Hellenic culture was being disseminated and established

throughout the civilized world by the conquests of Alexander and the expansion of the Roman Empire, the Greeks actively continued the development of astronomy, making particularly extensive use of the Babylonian results.

The great Greek astronomers Hipparchus (second century B.C.) and Ptolemy (second century A.D.) developed astronomy to the most advanced stage that was attained in ancient times; and for more than 1,000 years after the fall of the ancient civilization, no essentially new development or important further progress was effected in astronomy as left by the Greeks. Learning practically disappeared in the West, although a limited knowledge of Greek astronomy (obtained from old Roman writings) existed in some of the monasteries, especially after the eighth or ninth century; but at the declining Alexandrian school and among the nations of the East, Greek astronomy continued to be cultivated to a limited extent: Syriac versions of the Greek writings had been preserved among the Nestorian Christians, followers of the Syrian monk Nestorius who was exiled from Constantinople in the early fifth century, and whose missionaries founded religious institutions in many parts of western Asia; Greek astronomy had been carried to Persia by refugees from the Academy at Athens, closed by Justinian in 529; and in the pagan Harranian settlements the classical tradition still survived. Through these channels of diffusion, Greek learning was first transmitted to Baghdad after the rise of the Moslem Empire. Moslem astronomy, after the first impulse from India, was based wholly on the Greek writings—principally those of Ptolemy; and as transmitted by the Arabs to western Europe after the opening of the revival of learning, astronomy was substantially the same as when left by Ptolemy. The Arabs were accurate observers and skillful calculators; they contributed many new observations, tables, and treatises; and some of the Hindu and Arabic ideas which became integrated with the Greek knowledge, particularly in mathematics, were of great importance; but the improvements effected by the Moslems in astronomical science were only in details. Astronomy as slowly revived in Europe—first through Latin, Hebrew, and Spanish versions of Arabic astronomical and mathematical writings translated during the twelfth and thirteenth centuries, and later through the study of original Greek writings—was therefore essentially the ancient Greek astronomy as developed by Ptolemy (although the earlier and much less advanced ideas of Aristotle were also accepted to some extent); and modern astronomy emerged in western Europe directly through a progressive modification of the Ptolemaic astronomy. The impress of the Greeks and the Arabs is still apparent in the terminology of astronomy and uranography; and even traces of ancient Babylonian influence remain.

As the ancient astronomy gradually became known in Europe, the first active efforts to continue its development, and to remove the imperfections that became apparent, began during the fifteenth century—particularly in Germany, through the work of Peurbach (1423–1461) and Regiomontanus (1436–1476); but no important advances were made until, during the sixteenth and seventeenth centuries, Copernicus and Kepler transformed the Ptolemaic astronomy into a form which prepared the way for Newton and his successors.

The writings now surviving, which provide the original record of these ages of development, become fewer and more fragmentary the farther back in history we penetrate; the details of the earliest developments and mutual exchanges of ideas among different peoples are obscured by the mists of remote antiquity and cannot now be traced with certainty, while the beginnings are completely lost in the darkness of prehistoric times. The more conspicuous of the celestial phenomena that are immediately apparent to direct observation were undoubtedly among the first natural occurrences to be consciously noticed by primitive man; and even in prehistoric times the inhabitants of many different lands were led by one motive or another to begin astronomical observations and records. To early peoples, the starry heavens were an

intimate part of daily life and thought; celestial phenomena were the guide for numerous practical activities, and the basis of many popular customs. The cultivation of astronomy was not confined to the nearer Orient, where the particular development that has led to the learning of our own civilization had its beginning; and the relations between the nearer Orient and the ancient civilizations in India and eastern Asia, where the other principal cultural developments originated,[6] are imperfectly known, but apparently the development of ideas in western Asia and the Mediterranean region was not significantly influenced by the eastern Asiatic peoples. Astronomy was cultivated in China and India, beginning in very remote times—possibly extending back to the third millennium B.C. in China, and probably into the second millennium or farther in India—but in both regions it remained rather primitive until comparatively late times, and mostly independent of developments to the westward. Chinese culture may have been somewhat influenced in very remote times by Babylonia and possibly by ancient India, and it is certain that a trade connection existed between Sumeria and an early civilization in the Indus Valley that extended back to 2500 B.C. or earlier; but only very little is known either of the earliest part of the historic period in China (which does not open until about the fourteenth century B.C.) or of the period in India before 1500 B.C. Later, through contacts during the time of the Persian Empire and after the conquests of Alexander, learning was introduced into India from the westward; and in time some of the Hindu knowledge permeated to China, especially after the first century A.D. The earliest historic contact of China with the West was in the second century B.C., when the silk route to the Roman Orient was established; but at least a few ideas seem to have filtered through from Chaldea, Greece and possibly Persia as early as the fourth century B.C., and perhaps from India in the eighth century B.C. After the fourth century A.D., the development of Chinese astronomy was dominated by influences from the nations to the westward.

The earliest coherent Chinese astronomical writings now extant date from shortly before the Christian Era; the ancient astronomy recorded in them undoubtedly dates back in large part to at least 400 B.C., and includes some material that is several centuries older still. With some further development, this ancient system continued to prevail in China until the adoption of Western astronomy from the Jesuits in the late seventeenth century.[7] The Chinese astronomers directed their efforts almost wholly to the mere observation of celestial phenomena and the regulation of the calendar, and to the cultivation of astrology; during the thirteenth century, the influence of the Moslem Persians and Arabs penetrated to China, and observatories (superior to any in Europe at that time) were established (e.g., at Pekin) where observations with the ancient instruments were made for several centuries, but Chinese astronomical knowledge remained comparatively primitive, and astronomical science was never developed to an important extent. In India, however, a scientific Hindu astronomy had developed by the fifth or sixth century A.D., although some uncertainty exists as to the extent to which it developed independently of Greek influence; but progress ceased after the twelfth century, and a belated attempt (at Jaipur and elsewhere in north India) to revive activity in the early eighteenth century did not accomplish anything of importance.

The Hindus exerted an indirect influence

[6] The theme of the present discussion does not require any consideration of the astronomical knowledge which developed among the Maya, Aztec, and Inca civilizations, or among the different aboriginal and primitive peoples of various parts of the world. The astronomical ideas of some of these races are briefly described by E. ZINNER, *Geschichte der Sternkunde* (Berlin), 1931. For a summary of Mayan astronomy, see also: J. E. TEEPLE, *Maya astronomy*, Carnegie Inst. Washington Publ. 403, pp. 29–115, 1930; *cf.* MAUD W. MAKEMSON, *The Maya calendar*, Pop. Astron. **50**: 6–15, 1942. Some writers have advanced the speculation that the Chinese and the Mayan systems of astronomy had a common origin (see, e.g., Journ. Roy. Astron. Soc. Canada **33**: 1–4, 1939).

[7] See HERBERT CHATLEY, *Ancient Chinese astronomy*, Occas. Notes Roy. Astron. Soc. No. 5, pp. 65–74, June 1939.

on western astronomy by being the first nation to communicate astronomical knowledge to the Arabs and by contributing several important mathematical ideas; the principal Hindu astronomical writings are therefore of some interest for the present discussion. Of more direct interest are the principal Arabic treatises, particularly those which were most influential in the transmission of the ancient astronomy to the West during the Revival of Learning. The writings of greatest general interest, however, are: The outstanding Hellenic treatises that record the most important creative achievements of the Greeks; the Egyptian and more particularly the Babylonian records that served as the original foundation for the Greek developments; and the contributions from western Europe that transformed the ancient astronomy into modern form.[8]

THE CONTEMPORARY WRITINGS

No general treatise on astronomy is known from either Egypt or Babylonia. The astronomical knowledge of the ancient Egyptians must be inferred from the surviving inscriptions and pictorial representations of the heavens found on monuments and in the temples and tombs, from a few fragmentary manuscripts, and from the existing references (often untrustworthy) to Egyptian astronomy in Greek writings. Our knowledge of Assyro-Babylonian and Chaldean astronomy is derived principally from cuneiform clay tablets found in large numbers in the ruins of the temples and palaces, particularly in the great library where works of past ages were systematically assembled by the Assyrian king Assurbanipal at Nineveh in the seventh century B.C. The cuneiform astronomical tablets date from about 2000 B.C. to the beginning of the Christian Era, and are inscribed with records of observations, astrological omens, data on the rising, setting, and other phenomena of stars and constellations and calculated ephemerides of the moon and planets.

Many of the more important Babylonian astronomical tablets are reproduced in cuneiform and phonetic transcriptions, accompanied by German translations and explanatory discussions, in F. X. KUGLER, *Sternkunde und Sterndienst in Babel* (2 vols. and 3 supplements, Aschendorffsche Verlagsbuchhandlung, Münster in Westfalen, 1907–1935; the third supplement was prepared by J. Schaumberger, after Kugler's death in 1929); and an examination of representative examples of these original texts is the best way of obtaining a satisfactory idea of Babylonian astronomy.[9] The Babylonian ephemerides were based on empirical rules deduced from long observation of celestial phenomena; auxiliary tables and occasional precepts for computing the ap-

[8] An essential factor in the progress of astronomy was the development of appropriate mathematical methods for the treatment of celestial phenomena. Effective mathematical aids adapted to this purpose (other than ordinary numerical calculation) were not available until the Greeks formulated spherical geometry and the elements of trigonometry; the early development of these subjects was to a large extent directly in connection with astronomy. The Greeks were the first to construct an abstract logical system of mathematical knowledge, especially geometry; but, as in the case of astronomy, the development which led to the great mathematical achievements of the Greeks originated under Oriental influence. The Egyptians and especially the Babylonians made remarkable progress in elementary mathematics—principally in the solution of arithmetical problems, the formulation of rules for finding areas and volumes of geometric figures, and the solution of algebraic equations—but accomplished little in the way of general theorems or logical proofs. For a general account of Egyptian and Babylonian mathematics as recorded in extant papyrus manuscripts and cuneiform tablets, see O. NEUGEBAUER, *Vorlesungen ueber Geschichte der antiken mathematischen Wissenschaften, Bd. I: Vorgriechische Mathematik* (Berlin), 1934; and on Greek mathematics, Sir THOMAS L. HEATH, *Manual of Greek mathematics* (Oxford), 1931.

[9] For general accounts of Babylonian astronomy, see: J. K. FOTHERINGHAM, *The indebtedness of Greek to Chaldean astronomy*, Observatory **51**: 301–315, 1928 (rep. in Quellen und Studien Gesch. Math. Astr. u. Phys. **B2**: 28–41, 1932); A. T. OLMSTEAD, *Babylonian astronomy*, Amer. Journ. Semitic Lang. and Lit. **55**: 113–129, 1938; ZINNER, *Geschichte der Sternkunde*, pp. 33–69. On Babylonian influences in early Greek astronomy, *cf.* O. NEUGEBAUER, *On some astronomical papyri and related problems of ancient geography*, Trans. Amer. Phil. Soc. **32**: 251–263, 1942.

parent lunar and planetary motions are included among the cuneiform tablets, but in the absence of expository texts the methods of computation must usually be inferred from an analysis of the entries themselves. These ephemerides are characterized by being constructed with the aid of arithmetic progressions. The Babylonians were the first to represent the irregular motion of a celestial body as the mathematical resultant of a set of simple artificial components; the particular resolution of the actual motion into components that could be represented and compounded by arithmetic progressions was determined by the mathematical methods then available.

There is no treatise in which all the principal Egyptian records are reproduced and critically discussed, although a large number of examples of the inscriptions and pictorial diagrams are scattered through various publications. Typical examples of the Egyptian portrayal of the sky are reproduced in the Bulletin of the Metropolitan Museum of Art (New York), Feb. 1928 (Sect. II), and vol. 18, pp. 283–286, 1923; and in Isis **14**: 301–325, 1930, and **17**: 262–263, 1925. Examples of calendarial star tables are given in Osiris **I**: 500–509, 1936, and Isis **17**: 6–24, 1932. The noted Denderah planisphere has been reproduced in many books and articles (recently in The Sky, Dec. 1940). A facsimile and translation of a demotic papyrus showing a calculation of the dates of new moon will be found in Quellen und Studien Gesch. Math. Astron. u. Phys. **B4**: 383–406, 1938; and the extant tables of planetary positions (probably constructed from combined observations and calculations) have been edited and discussed by O. NEUGEBAUER, *Egyptian planetary texts*, Trans. Amer. Phil. Soc. **32**: 209–250, 1942. These lunar and planetary texts are from Roman times, but the methods seem to date from at least the first period of the Hellenistic age.[10]

The way in which Egyptian and Babylonian astronomical and mathematical knowledge was transmitted to Greece is incompletely known; many of the earlier Greek writings are lost, and hence the development of ideas cannot be completely traced, either among the early Greeks themselves or from the Greeks to their sources.[11] It is known, however, that many Greek scholars traveled extensively in foreign countries, especially Egypt; and that collections of Babylonian astronomical observations were sent to Greece after the capture of Babylon by Alexander (331 B.C.).

In the abundance of Greek writings that survive comparatively little has been preserved in original form. In general, the extant manuscripts are transcriptions made long after the works were originally written, and they require critical collation and editing by competent scholars before trustworthy versions of the ancient writings can be obtained. Some of the Greek writings have been found only in medieval Arabic translations. Arabic manuscripts—comprising many translations as well as original Moslem writings—survive in large numbers, especially in the Spanish archives, although many of them have not been carefully examined. In fact, museums and libraries contain a large quantity of source material for the history of learning among the ancient nations which has not yet been critically studied, while additional material is constantly being discovered through continued explorations in the Orient; and as these documents come to be studied, further vistas into the past may be opened up, although our historical knowledge must always remain more or less incomplete.

Many medieval Latin manuscripts—both translations of Arabic and Greek writings, and original Latin compositions—are in existence. With the invention of printing

[10] On Egyptian astronomy, see: ZINNER, *Geschichte der Sternkunde*, pp. 1–32; HERBERT CHATLEY, *Egyptian astronomy*. Journ. Egyptian Archaeol. **26**: 120–126, 1941; and O. NEUGEBAUER, Nature (London) **143**: 115, 1939. The book by E. M. ANTONIADI, *L'astronomie égyptienne* (Paris, 1934) is too uncritical to be a source of reliable information and does not take account of recent important discoveries, but the extensive collection of citations from Greek and Roman writers that it includes is of interest; Antoniadi greatly exaggerates the achievements of the Egyptians and the extent to which the Greeks were indebted to them.

[11] On early Greek astronomy (to about 250 B.C.), see Sir THOMAS HEATH, *Aristarchus of Samos* (Oxford), 1913.

about 1450, astronomical works, both ancient and contemporary, were printed in great numbers; the ancient works were issued in the original tongues and in Latin translations. These early editions, as well as the original editions of many later writings, are of course now rare; but most of the more important astronomical writings of past times (including those of the Hindus) are now available in comparatively recent editions, usually in both the original language and a translation into a modern language, although many have not been translated into English. A few are available only in old scarce editions; and some still do not exist in a modern language.

In reviewing the writings that have been most influential in the development of astronomical thought—either because they constitute especially significant advances in the evolution of ideas that have directly led to our own learning, or because they were widely accepted as standard sources of information—we shall list the most easily obtainable good editions of each, including in general both the original text and a translation into a modern language.[12]

From among all astronomical writings, there is little difficulty in selecting three outstanding treatises which rank foremost in fundamental importance for the historical evolution of modern astronomy, and which may be recommended to the general reader for first attention. The first of these works is the *Syntaxis mathematica* of PTOLEMY, usually referred to as the Almagest; written in the second century A.D., it remained for 1,400 years the almost universally accepted standard authority, and upon it were based practically all other important astronomical writings during this period. The Almagest occupies a position in astronomy corresponding to that of Euclid's *Elements* in geometry. Ptolemy collects and systematizes the astronomical knowledge that had been developed by his predecessors, and amplifies and extends it by his own contributions; his treatise forms a comprehensive account of the final stage to which astronomy was developed in ancient times. The second of the three treatises is the *Astronomia nova* of KEPLER, 1609, which constitutes the first fundamental advance in astronomical ideas that was accomplished after Ptolemy; it records the results obtained from Kepler's study of Tycho Brahe's observations, including the first two laws of planetary motion. The third is the *Philosophiae naturalis principia mathematica* of NEWTON, 1687, which completed the foundation of astronomy; it gives the physical interpretation of Kepler's empirically derived kinematical laws, and provides all the theoretical principles necessary for the exact mathematical calculation of celestial phenomena. The entire development represented by these three treatises was completely effected without the aid of the telescope.

There are also a number of other writings which, for one reason or another, are of sufficient historical importance or especial interest to claim particular attention in the present discussion, some of which—e.g., the *De revolutionibus orbium coelestium* of COPERNICUS—will immediately occur to the reader; but from the viewpoint of their significance for the logical development of the fundamental principles of astronomy, the above three works overshadow all others.

[12] The original text is, of course, necessary for critical study and is desirable even for the general reader. An ability, if not actually to read a work independently in the original language, at least to follow the original intelligently with the aid of a translation adds immeasurably to the pleasure and satisfaction of the reader and greatly enhances his appreciation of the content; it is principally for the *expression of thought* contained in the ancient writings that they are now read, not primarily for factual information, and much of the character of the original is inevitably lost in even the best of translations by competent scholars, to say nothing of inferior translations. A sufficient reading knowledge of Greek and Latin for the purposes of the general reader of astronomical and mathematical writings does not offer any insurmountable obstacle to the earnest student. Arabic presents more difficulties, while the Egyptian (hieroglyphic, hieratic, and demotic) and cuneiform must usually be left to specialists, but a knowledge of the fundamental principles of these languages is an aid to the appreciative and effective use of the edited texts and translations prepared by Oriental scholars. On the Egyptian language, see O. NEUGEBAUER, *Vorgriechische Mathematik*, pp. 72–78; and ADOLF ERMAN, *Die Hieroglyphen* (Sammlung Göschen. Nr. 608), 2te aufl. (Berlin), 1923. On the cuneiform writing, see NEUGEBAUER, *ibid.* pp. 49–67; and BRUNO MEISSNER, *Die Keilschrift* (Samml. Gösch. 708), 2te aufl. (Berlin), 1922.

The most authoritative version of the Greek text of the Almagest is the edition by HEIBERG: *Claudii Ptolemaei opera quae exstant omnia Volumen I, Syntaxis Mathematica*, editit J. L. Heiberg (in 2 vols., 1154 pp. 6½×4½ in.), Leipzig (Teubner), 1898–1903. A German translation from Heiberg's text is available: KARL MANITIUS, *Des Ptolemäus Handbuch der Astronomie*, 2 vols., Leipzig (Teubner), 1912–1913. The Greek text accompanied by a French translation was published by the Abbé HALMA, 1813–1816; the original is now rare, but a photographic reprint has recently been issued: *Composition mathématique de Claude Ptolémée*, par M. Halma, réimpression facsimilé, 2 vols., Paris (Hermann), 1927. Halma's text, however, can not be regarded as definitive, and his translation is somewhat deficient in places. No English translation of the Almagest has been published.[13]

The 13 books of the Almagest contain an account of spherical astronomy, including the necessary principles of trigonometry, a discussion of precession, and a star catalogue; theories and tables of the motions of the sun, the moon, and the five planets, based on the hypothesis of excentrics and epicycles; the theory of solar and lunar eclipses; and a determination of the sizes and distances of the sun and the moon. Except for constructing the theories of the planets and discovering the lunar inequality now called the evection, Ptolemy probably derived the contents of the Almagest almost entirely from Hipparchus (though adding many extensions and improvements), and many of the results depend upon principles that had been established very early in the development of scientific Greek astronomy. This development had begun in the fourth century B.C.; the work of Eudoxus of Cnidos (408–355) constituted the transition from the early speculative period to the period of scientific investigation. Eudoxus wrote a systematic description of the recognized constellations and the phenomena of the heavens, developed the elementary principles of the geometry of the celestial sphere and through his hypothesis of homocentric spheres made the earliest known attempt to account quantitatively for the observed irregular motions of the sun, moon, and planets among the stars by means of a true physical theory; his astronomical writings, none of which have survived, were partly the basis of many of the later treatises and further developments through which astronomy gradually reached the stage represented by the Almagest.

The fundamental hypotheses of the Almagest, as stated by Ptolemy, are

> . . . that the firmament is spherical and moves as a sphere; and that the earth also is sensibly spherical in form, considered as a whole, while in position it lies at the middle of the universe as though it were the center, being in magnitude and distance relatively only a point with respect to the sphere of the fixed stars, and undergoing no change of place through motion.

These principles had long been a generally accepted part of Greek thought; they began to emerge during the sixth and fifth centuries B.C. among some of the Greek speculative philosophers of that period, and to replace the older fanciful cosmologies of the mythological period, although in general the astronomical ideas of the early philosophers were exceedingly primitive and differed greatly from one another.[14] The concept of the heavens as a complete revolving sphere, or series of concentric spheres, entirely surrounding the earth, was a part of several of the early philosophical systems; that the earth was located at the center in free space, without support, was held by Anaximander (*ca.* 611–547) and Parmenides

[13] For other astronomical writings of Ptolemy, see Vol. 2 of the above edition of the Opera Omnia: *Opera astronomica minora*, ed. J. L. Heiberg, Leipzig (Teubner), 1907. For a German translation of the treatise in which Ptolemy explains the principles of the stereographic projection, see Isis **9**: 255–278, 1927. Ptolemy is also noted for his treatise on geography, which is second in importance only to the Almagest, and which influenced geography as long and as profoundly as the Almagest influenced astronomy; on the important manuscripts and editions of the geographical treatise, see Isis **20**: 267–274, 1933; **22**: 533–539, 1935; and **30**: 328, 1939.

[14] The details of the astronomical ideas held by the different Greek philosophers prior to the time of Eudoxus will be found in HEATH, *Aristarchus of Samos*, pp. 1–189; and J. L. E. DREYER, *History of the planetary systems*, pp. 6–86 (Cambridge Press), 1906. Both of these books are now rare.

(early fifth century) among others; while the spherical form of the earth was taught by the Pythagoreans in the late sixth century B.C. (although it is uncertain whether Pythagoras himself adhered to this view) and by Parmenides (who recognized that the temperature zones of the earth arise from its sphericity). In many cases, these ideas appear to have been mere a priori opinions without much foundation; but empirical data and rational arguments in support of them were in time forthcoming as Greek knowledge continued to develop. The sphericity of the earth came to be generally accepted during the early fourth century B.C.; several estimates of its size were made, though on what basis is unknown. The first known actual measurement of the dimensions of the earth was by Eratosthenes (275–194); in Ptolemy's treatise on geography a later measurement by Posidonius (*ca.* 135–50) is adopted. In general, on the basis of the evidence then available, the earth was regarded as stationary at the center of the universe; but the Greeks explicitly recognized that conceivably the earth could be in motion and the observed motions of the heavenly bodies only apparent, and this hypothesis was definitely adopted by some; Philolaus (fifth century B.C.), e.g., maintained that the earth, in common with the sun and other heavenly bodies, revolves around a "central fire"; Heraclides of Pontus (fourth century B.C.) taught the axial rotation of the earth (and incidentally a motion of Mercury and Venus around the sun); and Aristarchus of Samos (fl. *ca.* 280 B.C.) advocated both a rotation of the earth and an orbital revolution around the sun. The basis for these ideas is uncertain, and they appear to have met with little acceptance in ancient times.

Spherical astronomy in the form found in the Almagest was the result of a development that had begun with Eudoxus or possibly even earlier. The oldest Greek mathematical writings now extant, however, are two small treatises by Autolycus of Pitane (fl. *ca.* 310 B.C.), one on the formal geometry of the rotating celestial sphere (though the celestial sphere is not mentioned by name) and the other on the diurnal and heliacal risings and settings and daily and annual periods of visibility of the fixed stars and zodiacal signs; both apparently were derived largely from a still earlier work on Spherics probably written by Eudoxus. The Greeks used the term "Spherics" for abstract spherical geometry developed specifically in a form for application in astronomy but without explicit reference to the celestial sphere; while the description of the actual aspects of the heavens was called "Phenomena." For the Greek text (79 pp., $6\frac{1}{2}\times4\frac{1}{2}$ in.) of the treatises by Autolycus, with a Latin translation, see F. HULTSCH: *Autolyci de sphaera quae movetur, de ortibus et occasibus*, Leipzig (Teubner), 1885; these treatises are also available in a German translation: *Autolykos, Rotierende Kugel und Aufgang und Untergang der Gestirne*, übersetzt von ARTHUR CZWALINA, Leipzig (Akademische Verlagsgesellschaft), 1931. The writings of Autolycus were one of the sources used by his younger contemporary, the geometer Euclid (323–285? B.C.), in preparing a treatise on *Phenomena*, of which the Greek text (56 pp., $6\frac{1}{2}\times4\frac{1}{2}$ in.) with a Latin translation, edited by H. MENGE, is included in *Euclidis opera omnia* ediderunt J. L. Heiberg et H. Menge, vol. VIII, Leipzig (Teubner), 1916; this treatise is devoted principally to the geometrical theory of the phenomena of the diurnal motion. These early works do not contain any trigonometry or any consideration of spherical triangles as such; the principal special circles of the celestial sphere are recognized—horizon, equator, tropics, ecliptic and its obliquity, etc.—but no reference is made to any system of coordinates. The systematic use of formal geometric coordinate systems, particularly ecliptic coordinates, on the celestial sphere, and the development and application of adequate observational procedures and mathematical aids, were apparently largely owing to Hipparchus, second century B.C.; only unimportant fragments of his writings now remain, but the Almagest provides an extended account of his accomplishments and results. Hipparchus effected many improvements in the instrumental equipment then in use, probably devising several of the

instruments himself; he began the development of trigonometry,[15] without which many necessary astronomical calculations were difficult or impossible except as aided by the use of a celestial globe or armillary sphere; and he systematically observed the celestial bodies, discovering the precession of the equinoxes (which apparently was never recognized by the Babylonians, though different authorities are not in agreement on this point), and constructing a catalogue of several hundred stars. Among the Greeks, observation, though not lacking, was always overshadowed by theoretical investigation; according to Ptolemy, practically no records of observations of the fixed stars existed prior to Hipparchus, except a few by Aristyllus and Timocharis in the early third century B.C. The star catalogue in the Almagest, extending the one compiled by Hipparchus, is the earliest existing record of the aspect of the fixed stars; and it is a primary source of the classic 48 constellations which, with the 40 others added in later times, still appear on modern charts of the heavens with the romantic legends of Greek and Roman mythology woven about them, although even in ancient Greek times the historical origin of most of these asterisms was already obscured by the mists of antiquity.[16] A critical edition of this star catalogue was issued by C. H. F. PETERS and E. B. KNOBEL, *Ptolemy's catalogue of stars* (Carnegie Inst. Washington Publ. No. 86), Washington, 1915. Ptolemy also gives a careful description of the course of the Milky Way among the constellations.

The Ptolemaic theory of the solar system was the culmination of a progressive development extending back to the period in the sixth century B.C. when the concept of rotating crystalline spheres, naturally suggested by the apparent celestial motions, was introduced by the early Greek philosophers. On the basis of this general concept, Eudoxus constructed the first geometric theory that attempted to represent quantitatively the details of the observed apparent motions of the sun, moon, planets and fixed stars; by means of a system of 27 revolving spheres with mutually inclined axes, he accounted for the diurnal motions, and for the paths and principal variations in speed of the sun, moon, and planets among the fixed stars. Shortly afterward Callippus modified this system by adding seven more spheres to improve the agreement of the theory with observation. Probably these spheres were generally regarded, not as material bodies, but only as abstract geometrical constructions for computing the motions; but Aristotle (384–322 B.C.), who further developed the theory[17] by add-

[15] The earliest trigonometrical treatise now extant is a work on Spherics written by Menelaus of Alexandria about 100 A.D.; the Greek original is lost, but Arabic and other translations survive. This work is a treatise on spherical trigonometry disengaged from stereometry and astronomy. See MAX KRAUSE, *Die Sphärik von Menelaos aus Alexandrien*. Abh. Ges. Wiss. Göttingen, Phil.-Hist. Kl., Dritte Folge, Nr. 17, Berlin (Weidmann), 1936, which includes the Arabic text and a German translation; and A. A. BJÖRNBO, *Studien ueber Menelaos' Sphärik*. Abh. Ges. math. Wiss. 14: 1–154, Leipzig (Teubner), 1902. Evidence exists that the development of trigonometry by Hipparchus, Menelaus, and Ptolemy was a natural continuation of Babylonian ideas; this development was continued by the Moslems, who incorporated some ideas from the Hindus. Trigonometry, insofar as it consists of the geometrical properties of plane and spherical triangles and methods for their numerical solution, was brought to essentially its present form by Regiomontanus (Johann Müller) and Peurbach in the sixteenth century. The Greeks inscribed angles in circles, and accomplished their calculations by means of the chords subtending central angles; the chord was replaced by the sine, and the other trigonometric functions added, in later times.

[16] The stars were grouped into constellations in very remote times among all peoples. Possibly the Greeks derived their constellations, at least in part, from the earlier ones of the Egyptians and Babylonians, of which our knowledge is incomplete and often uncertain. The oldest systematic description of the Greek constellations that has come down to us was written about 270 B.C. by the poet Aratus; it is based on an earlier treatise by Eudoxus. The Greek text (732 lines) and an English translation of the *Phaenomena* of Aratus, edited by G. R. MAIR, are included in the same volume of the Loeb Classical Library that contains the writings of Callimachus and Lycophron (London, Heinemann, 1921; now handled by the Harvard University Press); the excellent English translation published by Robert Brown, Jr., in 1885, is now difficult to obtain, but is reprinted in an astrological volume by A. E. PARTRIDGE, *The story of the heavens*, Seattle (Simplex Publishing Co.), 1936.

[17] See GIOVANNI SCHIAPARELLI (1835–1910), *Le sfere omocentriche di Eudosso, di Callippo e di Aristotele*, Scritti sulla Storia della astronomia

ing 22 more spheres to the system, explicitly considered them to be physical realities. As a theory of the physical constitution of the universe, the Aristotelian spheres continued to be rather widely accepted, not only in Greek and Roman times, but also during the Middle Ages[18]; in mathematical astronomy, however, they were gradually superseded by systems of moving excentric circles and epicycles. The theory of homocentric spheres could not satisfactorily account for some phenomena—in particular, as the Greeks recognized at an early period, the occurrence of annular eclipses and the great variations in brightness of the planets imply considerable variations in the distances of the moon and the planets from the earth. The conception of excentric and epicyclic motions in space—which is essentially only a modification of the concept of homocentric spheres—was applied by Apollonius of Perga (third century B.C.) to explain the apparent motions, though probably the idea had originated still earlier; and it was systematically employed by Hipparchus and Ptolemy, who regarded it, however, not as a physical reality, but only as a basis on which the motions of the sun, moon and planets could be represented and calculated by means of an abstract geometrical system. Ptolemy adopted Hipparchus's theories of the sun and the moon, extending the latter by including evection; and constructed corresponding theories and tables of the planets, for which the necessary observations had not been available to Hipparchus.

Ptolemy's theory of eclipses is taken substantially from Hipparchus, with some improvements. Naturally, at that time only vague and conflicting ideas prevailed in general as to the physical nature of the celestial bodies; but the correct explanations of the moon's light, the phases of the moon, and lunar and solar eclipses had been given by several philosophers of the sixth and fifth centuries, and were an accepted part of Greek elementary astronomy at the time of Aristotle (although apparently this knowledge was not widespread among the people, who looked upon eclipses with superstitious terror). From the theory constructed by Hipparchus, the time of a lunar eclipse could be predicted to within an hour or two, and that of a solar eclipse with somewhat less accuracy, but the magnitudes could be only roughly calculated.

As Ptolemy explicitly states, no way of determining the distances of the planets from the earth was available in ancient times. That the celestial bodies are not all at the same distance had long been evident from such phenomena as occultations and eclipses; and various orders of distance had been adopted by different writers on the basis of the indirect evidence then available. The traditional order adopted by Ptolemy —Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn—had been generally accepted since the second century B.C., and was based principally on the criterion of relative rapidity of apparent motions; the planets confined to limited elongations were separated from the others by the sun. The earliest ideas of the magnitudes of the distances

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antica (3 vols. Bologna, Zanichelli, 1925–1927): vol. 2, pp. 1–112 (first published in 1877). *Cf.* DREYER, *History of the planetary systems*, pp. 87–122; and HEATH, *Aristarchus of Samos*, pp. 190–224.

[18] Aristotle's extension of the theory of homocentric spheres was his principal contribution to the development of astronomy. His astronomical writings as a whole are of secondary importance and interest; he collected and systematized the best knowledge of his time, as he did in other subjects, but the Greek astronomy of that period was still in an undeveloped state and unfortunately was crystallized in this form in Aristotle's writings, to be persistently invoked during later centuries in support of doctrines that could no longer reasonably be considered tenable. Aristotle was primarily a speculative philosopher, and his voluminous writings include many obscurities and unfounded ideas, although they also contain evidence of independent and careful observation. The astronomical material (largely of a metaphysical character) is found principally in the second book of *De caelo;* but shooting stars, comets and the Milky Way are discussed in *Meteorologica* (Bk. I), and the system of planetary spheres (though not fully treated in any of Aristotle's own extant writings) is briefly described in *Metaphysica* (Bk. XI, ch. 8). Translations of all these treatises have appeared in *The works of Aristotle translated into English* published at Oxford (Clarendon Press); the Greek text of *De caelo* with an English translation by W. K. C. GUTHRIE, has been published in the Loeb Classical Library (Harvard Univ. Press, 1939); the passages from *Metaphysica* are quoted in HEATH, *Aristarchus of Samos*, pp. 194, 212, 217, and the other astronomical writings of Aristotle are discussed in chap. xvii.

were mere speculations or arbitrary surmises; the first known actual measurement was by Aristarchus, who determined the relative distances of the sun and the moon (and hence the relative diameters too) by observing the angular distance of the moon from the sun at the time of the quarter phase. Aristarchus also determined the relative diameters of the sun and the earth by a method based on the measurement of the angular breadth of the earth's shadow through observations of lunar eclipses. The Greek text (30 pp., 6×9 inches) of Aristarchus's treatise "On the Sizes and Distances of the Sun and the Moon," with an English translation, is included in Sir THOMAS HEATH, *Aristarchus of Samos*, Oxford (Clarendon Press), 1913, a book unfortunately already rare. The eclipse method was further developed and applied by Hipparchus to determine the sizes and distances of the sun and the moon in terms of the earth's radius. These methods are perfectly sound; but the values obtained for the size and distance of the sun were greatly in error because of the difficulty of accurately measuring the necessary quantities, especially with the rough instruments then available, and their uncertainty seems to have been realized by Hipparchus. Ptolemy adopted the eclipse method to get the distance of the sun in terms of that of the moon; but he determined the distance of the moon by a parallax method. The values adopted in the Almagest for the size and distance of the moon are fairly accurate; but the value of 1210 radii of the earth for the distance of the sun was highly erroneous although it was not substantially improved until the solar parallax was determined by Richer and Cassini from observations of Mars in 1671–73.

After the appearance of the Almagest, many of the earlier writings continued to be extensively used in preparation for the study of Ptolemy's advanced and difficult treatise; several of them, in fact, were systematically gathered together into a collection that became known as the "Little Astronomy," in contradistinction to Ptolemy's great treatise to which they formed an introduction. This collection comprised: the works on Spherics by Autolycus and Euclid, already discussed; a later treatise on Spherics by Theodosius, who probably flourished about the beginning of the first century B.C., but whose works are largely compilations that have their source in Eudoxus or other early writers antedating Autolycus and Euclid; two other works by Theodosius—"On Habitations," relating to the aspects of the right, parallel, and oblique spheres, and "On Days and Nights," devoted principally to the variations of the lengths of day and night and the location of the sunrise and sunset points in relation to the position of the sun in the ecliptic; Euclid's "Optics"—a treatment of elementary perspective; Aristarchus's treatise on the sizes and distances of the sun and the moon; Hypsicles's "On Ascensions" (early second century B.C.)—a rudimentary set of six theorems on the times of rising of the zodiacal signs, and the oldest Greek work wherein the (ecliptic) circle is divided into 360 parts; and Menelaus's "Spherics."[19]

Moreover, there were in ancient times several elementary general textbooks of considerable interest: Preceding the Almagest was the introductory treatise "Elements of Astronomy" commonly attributed to Geminus (fl. *ca.* 70 B.C.), although it may not be genuine. It is largely a compilation

[19] A critical edition of the works of Theodosius was recently issued by Heiberg and Fecht: J. L. HEIBERG, *Theodosius Tripolites sphaerica*, Abh. Ges. Wiss. Göttingen, Phil.-Hist. Kl., Neue Folge, 19, Nr. 3; RUDOLF FECHT, *Theodosii de habitationibus liber: De diebus et noctibus libri duo*, ibid., Nr. 4, Berlin (Weidmann), 1927. This edition gives the Greek text (148 pp. 6½×10 inches) and a Latin translation; a German translation of the Spherics by CZWALINA, *Theodosios von Tripolis Sphaerik*, is included in the same volume with the translation of Autolycus, previously cited; and a French translation has been published by PAUL VER EECKE, *Les sphériques de Théodose de Tripoli*, Bruges (Desclée de Brouwer), 1927, the introduction to which contains a list of the theorems from the other two treatises. Euclid's work on Optics (in vol. 7 of *Euclidis opera omnia*) has been translated into French by PAUL VER EECKE, *Euclide, l'optique et la catoptrique*, Paris et Bruges (Desclée de Brouwer), 1938. On Hypsicles, see K. MANITIUS, *Des Hypsikles Schrift Anaphoricos nach Ueberlieferung und Inhalt kritisch dargestellt*. (Dresden) 1888; *cf.* V. DE FALCO, *Beiträge zur kritischen Textgestaltung des Autolykos und des Hypsikles*, Quellen u. Stud. Ges. Math. Astr. u. Phys. B1: 278–300, 1930.

of common knowledge from the time just before Hipparchus, and shows an influence of the Stoic philosopher Posidonius; it includes a valuable treatment of the calendar, calendrical cycles and the exeligmos, and considers rather fully the zodiac, the constellations, the circles on the celestial sphere, the apparent motions of the celestial bodies, eclipses, the climatic zones of the earth, and other topics, but contains very little about the planetary theories. The Greek text (116 pp., 6¾×4½ in.) with a German translation was edited by CAROLUS MANITIUS: *Gemini elementa astronomiae*, Leipzig (Teubner), 1898. Cleomedes (probably first century B.C.) also wrote a summary of Stoic astronomy, based chiefly on Posidonius, which is of particular interest for the details it contains of the measurements of the earth by Eratosthenes and Posidonius, and the recognition of some of the effects of astronomical refraction. The Greek text (114 pp., 6½×4½ in.) with a Latin translation was issued by H. ZIEGLER: *Cleomedis de motu circulari corporum caelestium libri duo*, Leipzig (Teubner), 1891; and a German translation was made by ARTHUR CZWALINA: *Kleomedes Die Kreisbewegung der Gestirne*, Leipzig (Akademische Verlagsgesellschaft), 1927. A treatise "On the Mathematical Knowledge Needed to Read Plato," by Theon of Smyrna (second century A.D., nearly a contemporary of Ptolemy), includes a book on astronomy that forms a valuable supplement to the Almagest; it is largely a compilation from Adrastus and Dercyllides of knowledge at the time of Hipparchus. The Greek text (165 pp., 6×9½ in.) with a French translation was edited by J. DUPUIS: *Théon de Smyrne, philosophe platonicien, exposition des connaissances mathématiques utiles pour la lecture de Platon*, Paris (Hachette), 1892. A later textbook, introductory to the astronomy of Hipparchus and Ptolemy, particularly the theories of the sun, moon, and planets, was written by Proclus (410–485 A.D.); the Greek text (119 pp., 6¾×4½ in.) with a German translation was published by CAROLUS MANITIUS: *Procli Diadochi hypotyposis astronomicarum positionum*, Leipzig (Teubner), 1909.

The Almagest, like many ancient writings, was the subject of later commentaries, which often are especially valuable for the historical details, and the extracts from earlier writings now lost, which they contain but which are usually very tedious reading. Among the writings of Pappus of Alexandria (probably end of third century A.D.) is a commentary on the Almagest, of which only Books V and VI are known to have survived; Theon of Alexandria (late fourth century A.D.), the father of Hypatia, wrote another commentary, which incorporates much of the one by Pappus. An edition of the Greek text of these two commentaries (with valuable notes) is being issued by the Abbé ROME, *Commentaires de Pappus et de Théon d'Alexandrie sur l'Almageste:* Tome I, *Pappus d'Alexandrie, commentaire sur les livres 5 et 6 de l'Almageste*, Rome (Biblioteca Apostolica Vaticana), 1931; Tome II, *Théon d'Alexandrie, commentaire sur les livres 1 et 2 de l'Almageste*, Vatican City (Bibl. Apost. Vat.), 1936. The introductions to these volumes include an explanation (in French) of the tables in the Almagest. Of commentaries on other writings, the one by Simplicius (sixth century A.D.) on Aristotle is especially valuable to the historian; it has been edited by J. L. HEIBERG: *In Aristotelis de caelo commentaria* (Berlin, 1894).[28]

The few Roman astronomical writings contain nothing original and are of little scientific importance. Pliny's famous "Na-

[28] In chronological order, the authors of the extant Greek writings of which editions have been cited in the foregoing discussion are:

B.C.		A.D.	
384–322	Aristotle	ca. 100	Menelaus
Fl.ca.310	Autolycus	2nd cent.	Ptolemy
323–285?	Euclid	2nd cent.	Theon of Smyrna
Fl.ca.280	Aristarchus	Late 3rd cent.?	Pappus
Fl.ca.275	Aratus	Late 4th cent.	Theon of Alexandria
2nd cent.	Hypsicles	410–485	Proclus
Ca. 100?	Theodosius	6th cent.	Simplicius
1st cent.?	Cleomedes		
Fl.ca.70	Geminus		

Brief extracts (in English) from some of these and a number of other Greek writers are given by HEATH, *Greek astronomy*, New York (Dutton), 1932. See also the delightful little volume by D'ARCY W. THOMPSON, *Science and the classics* (Oxford Univ. Press), 1940.

tural History" contains an interesting section (Bk. II) devoted to astronomy (available in the Loeb Classical Library), and several other compilers and commentators wrote on the subject.

The respects in which the Ptolemaic astronomy is now known to be defective have been much overemphasized in modern textbooks and popular writings, to the neglect of its intrinsic merit and its great importance as a foundation for the later development of modern astronomy. Greek astronomy, especially from the time of Hipparchus on, was for the most part developed according to sound scientific principles, by means of mathematical reasoning based on observational data that extended over many centuries. A high degree of success was achieved in the progressive formulation of theories by which celestial phenomena could be represented and calculated as accurately as they were then known from observation. For this purpose, the adoption of the geocentric hypothesis rather than the heliocentric is logically of secondary importance; and the system of excentrics and epicycles as a formal mathematical method is in principle above criticism. Besides, the planetary theory is not the whole of even the ancient astronomy; and a number of passages in the Almagest may easily be recognized as occurring in practically unchanged form as an integral part of modern treatises, while many other sections have merely now been superseded by material entirely equivalent but in a more refined or expeditious form. Of the physical arguments in the Almagest, few can justly be characterized as absurd. Ptolemy insisted on the physical reality of the fixity of the earth at the center of the universe, but only after express recognition and consideration of the evidence then available for other possibilities; some of the arguments by which he supported his hypothesis are scientifically unsound, but the others, though now recognized to be untenable, were entirely reasonable in the state of physics and mechanics at that time. There is ample evidence that the Greek scientific astronomers, unlike the early speculative philosophers, regarded their systems of spheres and epicycles, however, as nothing more than abstract geometrical constructions for conveniently representing and calculating celestial motions. The Almagest is an enduring monument to the genius of the ancient astronomers; and moreover it was through the explicit further development and revision of ancient astronomy in the form left by Ptolemy—not through its replacement by independent developments—that modern astronomy was constructed.

A change from the geocentric basis to the heliocentric is easily made without otherwise essentially altering the Ptolemaic system, and was the first of the successive modifications through which the Ptolemaic theory was transformed into the modern structure. This simple change of reference basis was made by Copernicus (1473–1543), and is the only important respect in which the Copernican system differs from the Ptolemaic; the traditional system of excentrics and epicycles is retained practically unchanged except for the simplification resulting from the reduction in the number of circles needed, 34 being used altogether, while the mathematical demonstrations and calculations in the Almagest are not fundamentally affected. The significance of the Copernican theory is as a transition between ancient and modern astronomy; as a contribution to the planetary theory, it was neither an original concept nor an important advance; and even the practical gain for computation was not great, either in convenience or in improved accuracy of the representation of phenomena. The celebrated treatise by Copernicus is expressly only a formal revision or reconstruction of the Almagest, in which Ptolemy is followed in the main with great fidelity and no basic new empirical considerations are introduced. An exceptional understanding of Ptolemy's principles and methods enabled Copernicus to adapt them to the heliocentric hypothesis, and to initiate the fundamental criticism and reconstruction of astronomy for which a need had long been apparent.[21] The Almagest had first

[21] See A. ARMITAGE, *Copernicus*, London (Allen

become generally known in the West through a Latin translation completed in 1175 by Gerard of Cremona from an Arabic version. The Moslem astronomers had already perceived that the tables based on Ptolemy's theories were frequently at variance with observations; and some of the later Moslems had attempted to return to Aristotle's system of material spheres or to introduce various makeshifts. During the general revival of learning, the diverse and conflicting hypotheses encountered in the different Greek writings and the rise of the authority of Aristotle (whose astronomical writings were first introduced in the West at the end of the twelfth century), together with the disagreements among the different tables that had been constructed and the failure of any of them to represent celestial phenomena accurately, led to many further attempts to improve on Ptolemy or to substitute other theories, although many of the fanciful ideas which were advocated could not seriously profess to account for the details of the celestial motions. These attempts persisted into the sixteenth century; Fracaster, for example, in 1538 used an Aristotelian system of 79 revolving crystalline spheres. In general, however, Aristotle did not gain the supremacy in astronomy, especially among the learned, that he attained in many other fields of thought from the thirteenth century until the Renaissance; nor was any appreciable success achieved in attempting to improve on the Ptolemaic system. Astronomy at the time of Copernicus was essentially still where Ptolemy had left it.

A facsimile reprint of the original Latin edition of Copernicus's treatise has been issued: *Nicolai Copernici Torinensis de revolutionibus orbium coelestium libri VI, 1543*, Paris (Hermann), 1927. The best text, however, is that of the third edition (Amsterdam, 1617; reprinted in 1640). A new Latin edition, printed from the original manuscript, was issued at Thorn in 1873 on the occasion of the 400th anniversary of the birth of Copernicus. Other than a rare Latin-Polish edition (Warsaw, 1854), the only complete translation into a modern language is a German version by C. L. MENZZER: *Nicolaus Coppernicus aus Thorn ueber die Kreisbewegungen der Weltkörper*, Thorn 1879 (rep. Leipzig, Akad. Verlagsges. 1939); but the first 11 chapters of Book I may be obtained in a French translation accompanied by the Latin text: A. KOYRÉ, *Nicolas Copernic, des révolutions des orbes célestes*, Paris (Alcan) 1934 (this edition contains a number of misprints and some errors of translation). The general reader may be more interested in the much briefer and simpler *Commentariolus*, which (together with the *Letter against Werner* and the *Narratio Prima* of Rheticus) is translated into English, with many helpful notes, in EDWARD ROSEN, *Three Copernican treatises*, New York (Columbia Univ. Press), 1939.

The diffusion and general acceptance of the Copernican hypothesis were very gradual. For a long time, the Copernican and the Ptolemaic systems were both in use as formal means for the calculation of ephemerides; the tables based on the Copernican theory were widely used for this purpose even when the theory itself was but little accepted. Copernicus definitely insisted on the physical truth of his hypotheses of the revolution and the rotation of the earth, and sought to establish them exclusively on the basis of astronomical data, but his arguments were not logically conclusive. The conflicts and inconsistencies that had existed for ages between efforts to determine the physical structure of the planetary system and attempts to construct tables that would represent observations, and the failure of mathematical astronomy to exert much influence on prevailing philosophical and theological views, continued throughout the Middle Ages, especially during the periods when the hostility and intolerance of the Church made it unsafe in many places to declare adherence to the new doctrines; and of course at all times in history many backward ideas prevailed among people at large. The telescopic discoveries by Galileo (1564–1642), especially his detection of the satellites of Jupiter and

and Unwin), 1938; and GRANT MCCOLLEY, *The eighth sphere of Copernicus*, Popular Astronomy 50: 133–137, 1942.

the phases of Venus, provided the first new evidence in support of the Copernican doctrine, and helped to establish the heliocentric theory through their immediate popular appeal; but Galileo did not take any direct part in the development of the planetary theory, nor were his arguments in favor of the Copernican ideas logically effective. During more than 200 years after the death of Copernicus, both the Ptolemaic and the Copernican systems continued to be taught in many places.

Meanwhile, in the sixteenth century the obvious need for additional and more accurate observations on which to base the development of improved theories and tables led to widespread activity in observational astronomy, carried on by means of the ancient instruments. The first improvements of consequence that had been effected in methods and instruments of observation since the time of Hipparchus and Ptolemy were accomplished by Tycho Brahe (1546–1601), who was the earliest observer to estimate and allow for instrumental errors and the effects of refraction, and to realize the importance of *continuous* records of the positions and motions of *all* the celestial bodies. He attained a much greater degree of accuracy in his observations than had ever before been achieved; he redetermined all important astronomical constants except the solar parallax, and constructed the last important star catalogue of the pretelescopic era.[22] Tycho's magnificent series of observations of the sun, moon and planets, when compared with the contemporary tables and ephemerides, demonstrated the insufficiency of all existing theories; and from a detailed analysis of these observations, especially those of the planet Mars, Kepler (1571–1630), in a prolonged systematic search for an hypothesis that would satisfy them, finally derived, by successive trial of one hypothesis after another, both geocentric and heliocentric, his three laws of planetary motion, modifying the Copernican excentrics to ellipses and formulating the laws governing the motions of the planets in these ellipses. The first two laws were explicitly established for Mars from the observations, but their validity for the other planets and for the moon was mostly assumed; the third law was demonstrated for the planets and for Jupiter's satellites.

Kepler's complete writings (mostly in Latin) fill eight large volumes[23]; but the greater part is a curious mixture of science, pseudoscience and mysticism, including astrology. From the viewpoint of scientific astronomy, there is comparatively little of value except in the *Astronomia nova seu physica coelestis tradita commentariis de motibus stellae Martis* and the *Epitome astronomiae Copernicanae*. In his first published work, the *Prodromus dissertationum cosmographicarum continens mysterium cosmographicum* (1596), Kepler compares the Ptolemaic and Copernican systems, stressing the greater simplicity of the latter; and constructs his fanciful planetary system based on the five regular solids.[24] Later, he derived his first two laws of planetary motion in the *Astronomia nova* (1609), which also contains a qualitative foreshadowing of the law of gravitation; for a German version of this great treatise, see *Johannes Kepler Neue Astronomie* uebersetzt und

[22] A definitive edition of Tycho's complete works (in Latin), including his letters and the records of his observations, has been edited by J. L. E. DREYER, *Tychonis Brahe Dani opera omnia*, 15 vols., Hauniae (Libraria Gyldendaliana), 1913–1929. The contents of the principal writings are described in some detail in the biography by DREYER, *Tycho Brahe*, Edinburgh (Black), 1890. Tycho's contributions to theoretical astronomy were comparatively unimportant, but for historical completeness his planetary system (*Opera* 4: 155–170) should be mentioned. Of especial interest to the general reader are the descriptions of Tycho's instruments and methods of observation in the *Astronomiae instauratae mechanica* (*Opera* 5: 1–162), and the nature of the observations that he took (which fill T. X–XIII of the *Opera*). On the improvements that he introduced into trigonometrical calculation, see DREYER, Observatory 39: 127–131, 1916.

[23] *Joannis Kepleri astronomi opera omnia* edidit Ch. Frisch, 8 vols., Frankfurt (Heyder & Zimmer), 1858–1871. A new edition of the original text of Kepler's works is now in course of publication: *Johannes Kepler Gesammelte Werke*, hrsg. von Walther von Dyck† und Max Caspar, Munich (Beck), 1937–.

[24] This work has been translated into German by MAX CASPAR, *Johannes Kepler Mysterium Cosmographicum—Das Weltgeheimnis*, Augsburg (Filser), 1923.

eingeleitet von Max Caspar, München-Berlin (Oldenbourg) 1929. The third law appears in the *Harmonices Mundi* (1619), which has also been translated by CASPAR: *Johannes Kepler Weltharmonik*, München-Berlin (Oldenbourg) 1939. The *Epitome astronomiae Copernicanae*, 1618 (*Opera*, VI) is of particular interest as an attractive general summary of contemporary ideas and for the information it contains on the historical development of astronomical terminology.

The *Tabulae Rudolphinae* prepared by Kepler for the calculation of ephemerides appeared in 1627, superseding the *Tabulae Prutenicae* (1551), which had been constructed by Reinhold on the basis of the Copernican theory but which had effected little improvement over the medieval tables based on the Ptolemaic astronomy.

Very few of Kepler's contemporaries fully comprehended and appreciated his work; and the general acceptance of his results, even among the adherents of the Copernican doctrine, was very slow, especially on the Continent. Meanwhile, many fruitless philosophical speculations were proposed such as the vortex theory of Descartes.

Kepler's Laws are simply empirical statements describing the way in which the planets move, inferred directly from observations. These laws do not explain the planetary motions, but they suggest that an influence of some kind is exerted on the planets by the sun; this fact was realized by Kepler, and the same idea had also occurred to many others who had speculated on the cause of planetary motions—even the inverse square law, among others, had been suggested—but these ideas remained barren of results until the profound investigations by Sir Isaac Newton (1642–1727). The limited knowledge of mechanics which existed during ancient and medieval times related principally to statics; only confused and largely erroneous ideas prevailed as to the motions of bodies. The explicit formulation of the correct general physical laws to which motions of material bodies conform was begun by Galileo and completed by Newton; since the celestial bodies do not move in the straight lines which, according to the Laws of Motion, are characteristic of motions undisturbed by the action of external forces, it was natural to infer that the moon and the planets are acted upon by forces of attraction. It had, of course, long been realized that the earth exerts an attraction on all bodies at its surface; and the laws of the motion of bodies falling under the action of this attraction had been investigated by Galileo. Newton demonstrated (1) that the force which holds the moon in its orbit around the earth is identical with the force which causes bodies near the surface of the earth to fall; and (2) that the law to which this force conforms is of the inverse square type. On this basis, Newton formulated the hypothesis of universal gravitation, and systematically applied it to explain the celestial motions; in particular, he showed that all three of Kepler's Laws may be deduced from this principle alone, and he accounted for many of the irregularities in the motion of the moon that had been known from observation since ancient times.

The original Latin editions of Newton's monumental treatise are, of course, now all rare. The first edition appeared in 1687, the third in 1726: Sir ISAAC NEWTON, *Philosophiae naturalis principia mathematica*, Editio tertia, London, 1726. The third edition was reprinted in 1871: *Sir Isaac Newton's Principia reprinted for Sir William Thomson and Hugh Blackburn*, Glasgow, 1871. A fine English translation (from the third edition) is now easily accessible: FLORIAN CAJORI, *Sir Isaac Newton's Mathematical principles of natural philosophy and his system of the world* (Motte's translations revised), Berkeley (University of California Press), 1934. The first two Books of the Principia are devoted to the motions of bodies in general, while in the third Book these general results are applied to the phenomena of the solar system: the *System of the world* is a nonmathematical summary of the material in the third Book of the Principia. Newton probably obtained many of his results with the aid of the Infinitesimal Calculus which he had devised, but in the Principia the work is recast into the

customary geometric form of the time.[25]

The Principia is the culmination of the long development, beginning in remote antiquity, through which the fundamental ideas and principles of modern astronomy gradually were progressively evolved and established. In this development, each successive outstanding advance was based directly and explicitly on the accumulated learning from the past. The great Babylonian astronomers Naburianos and Cidenas relied on the preceding centuries of observations; Hipparchus based his work on the Babylonian data and results, and on the ideas of his Greek predecessors; Ptolemy extended and completed the work of Hipparchus; fourteen centuries later Kepler, on the basis of Tycho Brahe's observations and with the aid of mathematical theorems developed 18 centuries previously by the Greek geometer Apollonius, completed the revision of the Ptolemaic astronomy that had been begun by Copernicus, and laid the foundation on which the Newtonian system has been erected. The Babylonians had analyzed the observed apparent planetary motions empirically, in terms of numerical progressions; the Greeks represented these motions by means of geometric theories in which the complex apparent movements were resolved into combinations of component uniform circular motions in space—first by the Eudoxian device of homocentric spheres, later by systems of excentrics and epicycles. The Greek geometrical procedures are entirely comparable to modern analytical methods—the terms of the infinite trigonometric series now used in formal calculations are the algebraic counterparts of the ancient geometric epicycles and deferents—but the Greek system was not adapted to the extension necessary to take into account all the irregularities subsequently revealed as observations accumulated. In the evolution of ideas, from the *empirical rules* for the apparent motions on the sky derived by the Babylonians, through the successive formal *geometric theories* of the motions in space constructed by the Greeks and, centuries later, by Copernicus, to the *kinematical laws* of Kepler and the *physical theory* of Newton, each stage is explicitly founded on a revision of previous systems, largely conserving the learning of the past but incorporating further developments of ideas that often had begun to emerge long before. A familiarity with the theories of Hipparchus and Ptolemy, especially with the terminology of the Ptolemaic theory, is essential to a proper understanding of the work of Copernicus and Kepler and to a full comprehension of the evolutionary development and the basis of modern astronomy. In the writings of each outstanding contributor, we find frequent explicit references and acknowledgements to his great predecessors, connecting modern astronomy directly with its beginnings in the past by a continuous chain of thought extending back nearly 30 centuries to the ancient Babylonian and Egyptian observers.

During the long stationary period following Ptolemy, the Moslem astronomers, in addition to translating the Greek works, wrote numerous original treatises and compiled many new tables; and the more outstanding of these writings, though containing no fundamental advances, are of great interest and importance as having been standard and widely used works among the Moslems and as being the medium through which western Europe first became acquainted with the ancient astronomy.

The initial source of Arabic knowledge was principally the Hindu learning, which had its origin in extreme antiquity. In remote times the inhabitants of ancient India, profoundly impressed by the beauty of the heavens, cultivated astronomy as a sacred duty. The beginnings of Indian astronomy—in the form of a rudimentary and often inaccurate acquaintance with the simplest aspects of celestial phenomena, a rough calendar, and a crude cosmology—are found in the Vedas, and in the Brāhmaṇas and Jyōtiṣas annexed to the Vedas; the earliest known formal astronomical treatise is the Vedāṅga Jyōtiṣa, probably

[25] A useful analysis of Newton's investigations and results is given by W. W. ROUSE BALL, *An essay on Newton's "Principia."* London (Macmillan), 1893; now rare.

dating from about 1400 B.C. and devoted mostly to a calendar for use in the regulation of religious ceremonies. The successive Vedic, and post-Vedic or Jaina, writings reflect a gradually increasing knowledge of the principal fixed stars and asterisms, the planets, the phenomena of the diurnal motion, and the apparent motions of the sun, moon, and planets through the zodiac; and improved calendars and systems of chronology were devised; but until a century or more after the opening of the Christian Era, Hindu astronomy remained very primitive and rudimentary, and not until about the fifth century A.D. did the scientific period in its development begin. It was brought to its most highly developed form during the interval from 500 A.D. to 1150 A.D.

Most of the Hindu astronomical writings prior to 500 A.D. have perished and are known only through fragments or through references and citations in other works. Many of the extant writings, in the form in which they now survive, have resulted from successive revisions and interpolations of older works, of unknown date and authorship, over a long period of time. It is uncertain how much of the content of the original older compositions is retained in the recensions now known; and the extent to which the progressive later developments were independent of influence from other nations, especially Greece, is somewhat controversial. A native Hindu astronomy unquestionably existed in remote antiquity and remained an important element in the learning of later times; but astronomical knowledge is known also to have been transmitted to India from other regions at several different periods during ancient times. There is archeological evidence that in the remote past, perhaps the early third millennium B.C., the earliest Indian civilization was influenced by Babylonia. Possibly contacts with China existed. In the time of Darius the Great, about 500 B.C., the valley of the Indus was a Persian satrapy; Alexander's invasion of India in 327 B.C., and the rise of the Greek kingdom of Bactria, established long enduring contacts with the Hellenic world. Probably, however, it must always remain more or less uncertain to what extent the origin and development of scientific astronomy in India were influenced by such Babylonian and Greek learning as may have been introduced. Some Greek knowledge was eventually incorporated into Hindu astronomy—Greek methods and Greek technical terms may readily be recognized in many of the Hindu writings; but apparently the Greek astronomy was transmitted in very imperfect and incomplete form. Often the Greek and the Hindu methods and numerical constants are quite different, but in many cases numerical values identical with Greek or Babylonian values are used. There can be no doubt that considerable original work was done in India, notwithstanding what may have been borrowed bodily or suggested by Greek and Greco-Babylonian ideas; but it is difficult to determine the extent to which Hindu astronomy in its final form represents a natural development of native elements and the extent to which it represents an assimilation and development of foreign ideas.

The earliest Hindu astronomical writings of a scientific character were the so-called Siddhāntas. A considerable number were originally composed sometime before 500 A.D., but the now surviving texts of the ones that have been preserved are later versions. The most important were the Brahma Siddhānta and the Sūrya Siddhānta. The content of some appears to have been drawn from a foreign source—the lost Romaka Siddhānta, as the name suggests, must have been an adaptation from some Greek or Roman work, and is known to have adopted for the length of the year the exact value used by Hipparchus and Ptolemy, while the Pauliśa Siddhānta may have been of Babylonian origin. In the Siddhāntas, the early mythological cosmologies are replaced by a spherical earth, unsupported and stationary in space.

The earliest extant text from the scientific period is the Āryabhaṭīya by Āryabhaṭa, who was born in 476 A.D. and with whom the most important period of Hindu astronomy begins. His treatise, composed in 499, is the oldest extant Hindu astronomical

text bearing the name of an individual author. An English translation with notes has been published by W. E. CLARK: The *Āryabhaṭīya of Āryabhaṭa*, University of Chicago Press, 1930; and another English translation, by PRABODH CHANDRA SENGUPTA, appeared in Journal of the Department of Letters (Calcutta University), vol. 16, 1927. The Āryabhaṭīya is a brief descriptive summary of the most distinctive principles of the author's own system of astronomy, not a detailed working manual of then existing astronomical knowledge in general, and it contains many imperfections; it is the earliest known Hindu text to include a section dealing specifically with mathematics. Āryabhaṭa based his treatise on the main principles of the older Siddhāntas, but systematized and further developed the subject; apparently he was largely the founder of scientific Hindu astronomy—his writings exerted great influence for many centuries, and were the basis for many subsequent developments by later Indian astronomers. He explained the planetary motions by means of a system of epicycles; whether the idea was original with him or borrowed from the Greeks is uncertain, but the Hindu system of epicycles differs in several important ways from the Greek theory. Āryabhaṭa also introduced into India the theory of the diurnal rotation of the earth, but this idea was rejected by other Hindu astronomers.

Āryabhaṭa was followed during succeeding centuries by several outstanding writers: Varāhamihira, early sixth century, was mainly a compiler; his Pañcasiddhāntikā, a summary of five of the older Siddhāntas, formed an exposition of all the more important astronomical doctrines current in his time. In the seventh century, Brahmagupta, one of the greatest of the Hindu scientists (although a severe critic of Āryabhaṭa), wrote two treatises which for many centuries were among the most widely used astronomical works in India; the earlier was the Brāhma Sphuṭa Siddhānta, a revised version of the old Brahma Siddhānta with some original developments by Brahmagupta incorporated, and the later was the Khaṇḍakhādyaka. An English translation of this second work, with notes and a series of appendices which provide a summary of Hindu astronomical ideas, has recently been issued by P. C. SENGUPTA: *The Khaṇḍakhādyaka, an astronomical treatise of Brahmagupta*, University of Calcutta, 1934. The most celebrated of the Hindu astronomers was Bhāskara or Bhāskarācārya, born in 1114; his greatest work, the Siddhānta S'iromaṇi, on mathematics and astronomy, was written about 1150, and like many of the other Hindu writings is based largely on late versions of the Sūrya Siddhānta.

The Sūrya Siddhānta is the foremost work among the astronomical writings of ancient India; it is a complete treatise on Hindu astronomy, and in somewhat modernized form it has remained a standard work in widespread use in India along with Brahmagupta's writings. The compilers of the Sūrya Siddhānta are unknown—it claims to have been revealed directly by the Sun about 2,165,000 years ago. The version now extant probably had taken form about 1100 A.D., and is a composite work founded on an original 800 or 900 years older. The monumental English translation and commentary by Burgess is a model of scholarly research, and indispensable in any study of Hindu astronomy; originally published in 1860 in the Journal of the American Oriental Society, it has recently been made again available: EBENEZER BURGESS, *Translation of the Sûrya-Siddhânta, a text-book of Hindu astronomy*, reprinted from the edition of 1860, edited by P. Gangooly, with an introduction by P. C. Sengupta; University of Calcutta, 1935. This version embodies considerable material drawn from Āryabhaṭa and Brahmagupta. A fantastic theory of the physical cause of planetary motions is included, and many of the methods give only approximate results, but on the whole the Sūrya Siddhānta is a sound and fairly accurate system of astronomical knowledge.

The Hindu works are written in Sanskrit verse, which is exceedingly difficult to translate and often is difficult to interpret after it has been translated; the style is so concise and elliptical that a copious com-

mentary, exceeding the original text in length, is usually required to make the text intelligible. For the most part the Hindu writings are simply collections of factual assertions and rules for solving problems, rather than formal expositions. The specific editions listed in the foregoing discussion have been confined to ones issued very recently; many of the other writings mentioned are also available in less easily obtainable publications, but those cited include the works of greatest general interest and are representative of Hindu astronomy. Much the same topics are covered in all the different treatises—rules for finding the mean and the true places of the planets with the aid of epicycles or eccentrics; solutions of a wide variety of problems in spherical and practical astronomy, including the use of the gnomon and the armillary sphere; methods for calculating conjunctions and other aspects of the planets, lunar and solar eclipses, the position of the moon's cusps, and heliacal risings and settings of stars and planets; the calendar, and systems of chronology; and descriptions of the constellations, particularly the zodiac.[28]

It was from the works of Brahmagupta that the Arabs first obtained a knowledge of astronomy: At the court of al-Mansur, in the eighth century, the Arabian scholars met the Hindu scientist Kankah, who acquainted them with Brahmagupta's treatises. Many of the Hindu writings were translated into Arabic. After the initial impulse, however, Moslem astronomy was based wholly on the ancient Greek writings —almost exclusively on Ptolemy; a knowledge of the Greek learning was first communicated to the Moslems at the court of Baghdad by Nestorian Christians from Khusistan at the head of the Persian Gulf

Among the great profusion of Arabic writings on astronomy, the treatise by al-Farghānī or Alfraganus, composed in the ninth century, was later one of the most influential in western Europe. The Arabic text (109 pp., 6×8 inches) with a Latin translation was edited by J. Golius: *Alfraganus, Elementa astronomica*, Amsterdam, 1669 (no later edition has been published). This treatise, based on Ptolemy, is an account of astronomy as known to the Moslems in the ninth century; it was translated into Latin in the twelfth century, and widely read in Europe until the time of Regiomontanus. The most outstanding of the Arabic treatises, however, was written by al-Battānī or Albategnius (*ca.* 857–929), one of the greatest of the Moslem astronomers. The Arabic text, with a Latin translation and extensive notes including a glossary of Arabic astronomical terms, has been edited by C. A. Nallino: *Al-Battānī sive Albatenii opus astronomicum*, Pubblicazioni del Reale Osservatorio di Brera in Milano, No. XL, 3 vols., 1899–1907. This treatise, likewise based on the Almagest but with improved tables and constants, was also extremely influential in western Europe until the time of the Renaissance.

The Moslems were ardent observers, and are particularly noted for their activity in the construction of instruments and the compilation of tables. The Arabic instruments and methods of observation and calculation were described by Aboul-Hassan Ali de Maroc, whose treatise has been translated into French: *Traité des instruments astronomiques des Arabes composé au treizième siècle par Aboul Hhassan Ali, de Maroc;* traduit par J.-J. Sédillot et publié par L. Am. Sédillot, 2 vols., Paris, 1834–1835; and *Supplément*, 1844. Among the masterpieces of Moslem observational astronomy is the systematic description of the constellations by Al-Sufi (903–986); a French translation, with parts of the Arabic text, was published by H. C. F. C. Schjellerup: *Description des étoiles fixes composée au milieu du dixième siècle de notre ère par l'astronome Persan Abd-al-Rahman al-Sūfi:* St.-Pétersbourg (l'Académie Impériale des Sciences) 1874. Cf. Metrop. Mus. Studies (New York), vol. 4 (pt. 2): 179–197, March, 1933. Of the Moslem astronomical tables, the more important were: the Hakemite Tables, compiled in Egypt by Ibn Jūnis (d. 1009), perhaps the greatest of the Mos-

[28] See the introductions and other explanatory material in the editions of the Hindu writings to which reference has been made. *Cf.* Sukumar Ranjan Das, *Scope and development of Indian astronomy*, Osiris II: 197–219, 1936.

lem astronomers; the Toledan Tables, which superseded the Hakemite Tables in the twelfth century; and the famous Alfonsine Tables, probably completed about 1272 under the patronage of King Alfonso X. The Alfonsine Tables, which remained the best available for 300 years, and the *Libros del Saber*, an encyclopedic compilation (in Spanish) of astronomical knowledge from Arabic writings (published at Madrid, 1863–1867, in 5 large folio volumes, by Don Manuel Rico y Sinobas) circulated widely through Europe and were of great importance in the revival of astronomy in the West.[27]

The Arabic writings in Latin translations were the principal source of information in western Europe until studies of original Greek manuscripts commenced to spread during the Renaissance; but original works began to be composed early in the Revival of Learning. The numerous astronomical books issued during medieval and early modern times are described in treatises on the history of astronomy; for the most part, they represent no significant advances, and are of importance chiefly to the historian. The principal elementary textbook of astronomy throughout medieval times was the *Tractatus de sphaera* or *Sphaera mundi* written about 1233 by SACROBOSCO, also known as John of Halifax or Holywood. It remained very popular for more than 400 years—it was one of the first astronomical books to be printed, and editions in great number continued to be issued until the middle of the seventeenth century; it is a rather crude little treatise, apparently derived from Alfraganus and Albategnius, on the rudiments of Ptolemaic astronomy, and is devoted principally to spherical astronomy; the contents are reviewed in some detail by WALTER B. VEAZIE, *Chaucer's textbook of astronomy: Johannes de Sacrobosco*, Univ. of Colorado Studies, Ser. B. 1: 169–182, 1940. During the transition period of the fifteenth to the seventeenth centuries, the textbooks which at first appeared were only summaries of Ptolemaic astronomy,[28] but during the latter part of the period an increasing number either included an account of both the Ptolemaic and Copernican hypotheses or else were explicitly based on the Copernican theory. Of especial interest to the general reader is the important exposition of contemporary astronomical knowledge from the Copernican point of view by KEPLER, *Epitome astronomiae Copernicanae* (1618), which has already been mentioned.[29]

[27] See J. H. REYNOLDS, *The Hakemite Tables of Ebn Jounis*, Nature (London), **128**: 913–914, 1931; ERNST ZINNER, *Die Tafeln von Toledo (Tabulae Toletanae)*, Osiris **1**: 747–774, 1936; J. L. E. DREYER, *The original form of the Alfonsine Tables*, Mon. Not. Roy. Astr. Soc. **80**: 243–262, 1920. After the decline of Moslem learning in Asia, astronomy was later temporarily revived in the East by Persian and Tartar astronomers under the Mongols. A great observatory was founded at Marāgha in northwest Persia, where extensive observations were made with magnificent instruments; and another important scientific center developed at Khānbaliq. The last of the Oriental astronomers was Ulug Begh (d. 1449), who worked at an observatory built at Samarkand in 1420; the tables which he compiled included the first star catalogue constructed from original observations since the time of Hipparchus and Ptolemy. See E. B. KNOBEL, *Ulugh Beg's catalogue of stars*, Carnegie Inst. Washington Publ. No. 250 (Washington), 1917.

[28] PEURBACH'S *Theoricae novae planetarum*, 1472, was especially noted, and editions continued to be issued for a hundred years. A rare work of this period, which, because of its unique character, deserves mention, is PETER APIAN, *Astronomicum Caesareum*, Ingolstadt, 1540, of which only 35 copies are known now to be in existence; it is described by S. A. IONIDES, Osiris **1**: 356–389, 1936 (*cf.* Publ. Astron. Soc. Pacific **46**: 325–338, 1934). The unique interest of the book lies in the numerous charts and combinations of rotatable paper dials it contains for graphically calculating celestial phenomena and solving astronomical problems; it is based on the Ptolemaic theory, and gives remarkably accurate results. The book also discusses Apian's noted discovery that the tails of comets always point away from the sun; and it contains the earliest printed planisphere (first published separately in 1536, and reproduced in facsimile in 1927 by L. Rosenthal's Antiquariat, Munich).

[29] Also of great interest is the earliest star atlas (though star maps and constellation figures had appeared in several earlier printed works): JOHANN BAYER, *Uranometria* (1603), with its 51 beautiful copper engravings of the constellations as drawn by Albrecht Dürer, in which the stars were for the first time distinguished by Greek letters. The next notable work of this kind, the great star atlas by FLAMSTEED, *Atlas coelestis*, was published at London in the eighteenth century, and a French edition with much smaller plates, edited by FORTIN, was issued at Paris. An important and worth-while element of the romantic charm of the night sky has been lost with the disappearance of the classic constellation figures from modern charts of the heavens.

During the course of the eighteenth century, textbooks and popular treatises came to be generally based on Newtonian principles, and the traditional content amplified by descriptive material obtained from telescopic observation; the first treatise based on gravitational principles was DAVID GREGORY, *Astronomiae physicae et geometricae elementa*, Oxford, 1702. Among the most widely used books, representative of the generally accepted astronomical thought of this period, were the numerous editions (during the 18th and early 19th centuries) of JAMES FERGUSON, *Astronomy explained upon Sir Isaac Newton's principles*, and the popular work by LALANDE, *Abrégé d'astronomie* (Paris, 1775).

With the establishment and general acceptance of the Newtonian system, the principal problem of astronomy became to deduce, from the Laws of Motion and the Law of Gravitation, the motions of the bodies in the solar system, and to account, on the basis of the Newtonian theory, for all the details of the observed apparent motions. As the precision of astronomical observations increased, many details of the celestial motions were revealed that had not appeared in Tycho Brahe's observations; and it is a remarkable fact that the Law of Gravitation both explains Kepler's Laws and at the same time immediately shows that these laws can be only first approximations, and had Tycho's observations been either a little less exact or a little more accurate Kepler could hardly have deduced his laws from them.

The development of Celestial Mechanics was initiated by the brilliant work of Clairaut, D'Alembert, Euler (whose *Theoria motuum planetarum et cometarum*, 1744, is the earliest analytical solution of the Problem of Two Bodies), and Lagrange. The first to undertake the systematic construction of complete gravitational theories for the motions of all the principal bodies of the solar system was LAPLACE (1749–1827), whose results are contained in his *Traité de mécanique céleste*. Laplace developed the equations to only a comparatively low order of approximation, but they demonstrated the agreement of the celestial motions with Newton's Law to at least the degree of accuracy that had then been attained in observational astronomy. The observations accumulated by Tycho Brahe, their coordination by Kepler into his empirical laws, the formulation of the hypothesis of universal gravitation by Newton, and the subsequent verification of this hypothesis through the comparison of the theoretical motions with observations form a classic example of Scientific Method.

Meanwhile, Bradley's discoveries of aberration (1728) and nutation (published 1748) had supplied in principle the necessary basis for attaining in practice the increased accuracy that became potentially possible with the continued refinement of instrumental equipment; and following Laplace, a need for further development of the theories of the celestial motions was soon provided by the introduction of a higher order of precision into the astronomy of position under the leadership of Bessel (1784–1846). With the work of Laplace and Bessel, which opened the prolific development of gravitational astronomy and positional astronomy during the nineteenth century, we may appropriately conclude the present survey. The latter part of the nineteenth century closes a very definite period in the development of astronomical science: The great era of Fundamental Astronomy, extending back to ancient Egypt and Babylonia, was over; and the rise of sidereal astronomy (initiated by Sir William Herschel in the latter eighteenth century) and astrophysics had begun.[30] We are now in the midst of the new period, in which astrophysics and studies of the sidereal and extragalactic systems are the fields of predominating interest and activity.

[30] Classical astronomy, as known in the nineteenth century, is well represented by Sir JOHN HERSCHEL, *Outlines of astronomy* (10th ed., 1869); SIMON NEWCOMB, *Popular astronomy* (5th ed., 1884); and C. A. YOUNG, *General astronomy* (rev. ed. 1904), all of which are still worthy of study. See also AGNES M. CLERKE, *Popular history of astronomy during the nineteenth century*, 4th ed., London (Black), 1902.

PALEONTOLOGY.—*Fossil Mammalia from the Almy formation in western Wyoming.*[1] C. LEWIS GAZIN, U. S. National Museum.

In the course of investigations for the U. S. Geological Survey in western Wyoming in 1936, J. B. Reeside, Jr., B. N. Moore, and W. W. Rubey discovered several localities for fossil vertebrate remains in beds regarded as the Almy formation. These exposures were of the deeper red beds stratigraphically below the Knight, and at certain places, as observed by Rubey, unconformably below this formation as it is exposed in the vicinity of the Green River in the southwestern part of Sublette County. Unfortunately all the materials were too fragmentary for certain identification, but in 1939 Rubey, with the assistance of John Rogers, succeeded in finding a lower jaw of a species of the primate *Plesiadapis* in Almy beds exposed along La Barge Creek, about 7 miles due west of the town of La Barge in Lincoln County. The writer visited several of these localities during the summer of 1941, and with the assistance of G. F. Sternberg and Franklin Pearce he was successful in securing additional material from the La Barge Creek locality and determinable remains, including a *Coryphodon* skull and a lower jaw of *Eohippus*, from exposures at a stratigraphically higher level about 9 miles north of the La Barge Creek occurrence.

The La Barge Creek locality, sections 1 and 12, T. 26 N., R. 114 W., has produced the following forms:

Plesiadapis rubeyi, n. sp.
Plesiadapis, cf. *cookei* Jepsen
Creodont, gen. and sp. undet.
Phenacodus almiensis, n. sp.
Ectocion sp.

The very incomplete fauna here listed suggests the Clark Fork stage, or uppermost Paleocene, indicated primarily by the *Plesiadapis* material, together with the presence and suggested predominance of *Phenacodus*. The beds at this locality are a reddish, pebbly clay, partly conglomeratic. They were mapped by A. R. Schultz[2] as the northward equivalent of the Almy formation and are so regarded by Rubey, who interprets this site as being several hundred feet stratigraphically below the top of the formation.

The more northerly locality mentioned above, in the upper part of one of the branches of Dry Piney Creek, sections 23 and 24, T. 28 N., R. 114 W., has yielded but two forms, and these have been tentatively identified as *Coryphodon radians* and *Eohippus index*. The beds here were mapped by Schultz as a part of the Knight formation; Rubey, however, considers the exposures as being of the uppermost part of the Almy and possibly including the limy layers regarded as representing the Fowkes formation. In any case the beds at this point seem definitely of lower Eocene age, or Wasatchian. The two forms encountered appear most closely related to corresponding types described by Cope from the vicinity of Evanston, Wyo., presumably out of the Knight. It should be further mentioned that a few miles north of La Barge and a short distance to the east of the Dry Piney Creek locality well developed, variegated exposures of Knight have produced a Lost Cabin fauna.[3]

There follows a systematic description of the materials discovered well down in the Almy as exposed along La Barge Creek and regarded as Clarkforkian or uppermost Paleocene:

Plesiadapis rubeyi, n. sp.

Fig. 1

Type.—Portion of right ramus of mandible with P_3-M_2, M_1 incomplete, U. S. N. M. no. 16696.

Horizon and locality.—Almy formation, NE¼SW¼ sec. 1, T. 26 N., R. 114 W., about 7 miles west of La Barge, Lincoln County, Wyo.

Specific characters.—A little larger than *P. gidleyi*. Lower cheek teeth long and relatively narrower than in *P. gidleyi*, particularly P_3, and

[1] Published by permission of the Secretary, Smithsonian Institution. Received March 26, 1942.

[2] SCHULTZ, A. R., U. S. Geol. Surv. Bull. 543, pl. 1. 1914.

[3] BONILLAS, YGNACIO, Journ. Mamm. 17: 139–142. 1936.

to a less extent P_4. Cusps of teeth more inflated and basins a little less broadly excavated. Anteroexternal cingulum about base of protoconid weaker on M_2. Paraconid and metaconid on M_2 of about equal height and slightly closer together than in *P. gidleyi*.

Fig. 1.—*Plesiadapis rubeyi*, n. sp. Right lower dentition, P_3 to M_2 inclusive, type specimen, U. S. N. M. no. 16696, lingual and occlusal views. ×3. Almy Paleocene, Wyoming. Drawing by Sydney Prentice.

Description.—Plesiadapis rubeyi, as indicated by the lower jaw portion, is a little larger than the Tiffany *P. gidleyi*, or than *P. dubius* of the Clark Fork. The Almy form differs from these two species principally in the actually and relatively greater anteroposterior length of the lower cheek teeth. These comparisons are facilitated by the statistics given by Simpson[4] for *P. gidleyi*. The deviation of the measurements of *P. rubeyi* from the mean of *P. gidleyi* divided by the standard deviation of *P. gidleyi* varies from +4.5 to +5.5 for the lengths of the teeth, but with no significant figures pertaining to the widths. The relation of length to width of teeth appears comparable to that in the Silver Coulee *P. fodinatus*, and the proportions of M_2 given by Jepsen[5] are very close to those in *P. rubeyi;* however, M_1 in the Almy form is strikingly smaller. No measurements were given for the premolars of *P. fodinatus*. *P. anceps* from the Scarritt Quarry[6] in the Crazy Mountain field is comparable in size with *P. rubeyi* but exhibits much shorter and simpler premolars and M_2 is relatively wider.

In P_4 of *P. rubeyi* the acute posterointernal ridge extending down the protoconid is somewhat deflected at a point about halfway down its length, suggesting an incipient metaconid. A very slight increase in the development of the anterior keel on P_4 immediately above the entoconid of P_3 might suggest a paraconid. The heel of P_4 is distinctly basined and exhibits two cusps, the hypoconid and entoconid. These cusps are also distinguished on P_3 but not so widely spaced.

TABLE 1.—MEASUREMENTS (IN MILLIMETERS) OF LOWER TEETH, NO. 16696, OF PLESIADAPIS RUBEYI

Measurement	P_3	P_4	M_1	M_2
Anteroposterior diameter	2.8	2.9	3.0*	3.7
Transverse diameter	1.9	2.2	2.7*	3.2

* Estimated.

The length of the preserved dentition, P_3-M_2 inclusive, is 12 mm.

Plesiadapis, cf. cookei Jepsen

A large form of *Plesiadapis* is represented in the collection from the La Barge Creek locality (SW¼ NE¼ sec. 12, T. 26 N., R. 114 W.) by the greater portion of a left mandibular ramus, U. S. N. M. no. 16698. The specimen includes P_3, most of P_4, M_2 complete, and a small portion of M_3. The teeth appear to be a little larger than in the type from the Clark Fork, as indicated by Jepsen's[7] measurements, and are relatively elongate, particularly the premolars. The difference in the latter respect from the type of *P. cookei* is probably less significant than this character was found to be in comparisons of *P. rubeyi* with related species.

P_3 and P_4 both exhibit a bilobed talonid, although this portion of P_4 is incomplete. The rugosity of the enamel on the anterolingual portion of P_4 gives rise to a suggestion of a paraconid, not developed to this extent, however, on P_3. Neither of these teeth shows any evidence of a metaconid.

In M_2 the metaconid, very close to the paraconid, is posterolingual to this cusp and joined by a ridge to the protoconid. The external cingulum on this tooth is not well developed and is in evidence only from the anterolateral portion of the hypoconid to an anterior position on the protoconid. The enamel on this tooth is somewhat rugose, most noticeably about the hypoconid and on the posterior wall of the trigonid.

[4] SIMPSON, G. G., Amer. Mus. Nov. 817: 3–7. 1935.

[5] JEPSEN, G. L., Proc. Amer. Philos. Soc. 69: 515–517. 1930.

[6] SIMPSON, G. G., Amer. Mus. Nov. 873: 19–20. 1936.

[7] JEPSEN, G. L., *ibid.*, pp. 525–528. 1930.

TABLE 2.—MEASUREMENTS (IN MILLIMETERS) OF LOWER TEETH, NO. 16698, OF PLESIADAPIS, CF. COOKEI

Measurement	P_3	P_4	M_1	M_2	M_3
Anteroposterior diameter	5.2	5.3	5.4*	6.4	10.*
Transverse diameter	3.7	...	...	5.5	...

* Estimated.

Creodont, gen. and sp. undet.

A portion of an upper cheek tooth, U. S. N. M. no. 16699, including the protocone or deuterocone but externally incomplete, is regarded as representing a form of creodont. A portion of one of the external cusps is preserved, presumably the metacone, in which case the tooth resembles the posterior and lingual portions of M^1 in a species of *Didymictis*. The protocone and cusp presumed to be the metacone are of about equal height, although the protocone appears much more robust, and the outer angle of the tooth is evenly rounded, not projecting.

Phenacodus almiensis, n. sp.

Fig. 2

Type.—Partial skeleton, including palatal portion of skull with canines and cheek teeth, P^3 to M^3, cervical vertebrae, and incomplete limb and foot bones, U. S. N. M. no. 16691.

Horizon and locality.—Almy formation, SW¼ NE¼ sec. 12, T. 26 N., R. 114 W., about 7 miles west of La Barge, Lincoln County, Wyo.

Specific characters.—Size small with cusps of teeth relatively acute, somewhat crescentic, and uninflated. Anteroexternal and posteroexternal angles of upper teeth moderately acute. Parastyle well developed on P^3 to M^3. Slight tetartocone and protoconule on P^3; prominent on P^4 with the addition of a weak, posteriorly placed metaconule. Hypocone well developed and lingual in position on all upper molars. Metaconule in line between metacone and hypocone. Mesostyle, metacone, and metaconule distinct on M^3.

Description.—*Phenacodus almiensis* is represented by a left maxillary portion, U. S. N. M. no. 16992, including P^4 to M^3, and two isolated upper teeth, in addition to the more extensive material comprising the type. The form appears to be appreciably smaller than any of the variants included in the *Phenacodus primaevus* group.[8] It is distinctly smaller also than the Tiffany *P. grangeri*[9] but a little larger than the Gray Bull forms, *P. copei* and *P. brachypternus*. Comparisons with the Tiffany *P. matthewi* and *P. gidleyi*[9] are not satisfactory, inasmuch as these are known only from lower teeth, and none was found of *P. almiensis;* however, the difference in size indicated by these lower teeth is significant.

Fig. 2.—*Phenacodus almiensis*, n. sp. Left upper dentition, P^3 to M^3 inclusive (M^3 drawn reversed from right side), type specimen, U. S. N. M. no. 16691, occlusal view. ×2. Almy Paleocene, Wyoming.

In comparison with material of the *Phenacodus primaevus* group, *P. almiensis* is seen to have much less inflated cusps, and these tend to be more crescentic in appearance, and the outer angles of the upper teeth are more acute. Also, the parastyles are better developed, and P^4 exhibits a weak metaconule. In these respects *P. almiensis* strongly resembles *Ectocion* but differs from members of that genus in important structural characters. That is, the metaconule of the upper molars is not forward in position but in line with the metacone and hypocone; also, the third upper molar is not triangular and has a rather well developed hypocone. The mesostyle, metacone, and metaconule of M^3 are less developed than in *Ectocion* but are more distinct than in *Phenacodus*. The

[8] See MATTHEW, W. D., and WALTER GRANGER, Bull. Amer. Mus. Nat. Hist. 34: 332–348. 1915. See also SIMPSON, G. G., Amer. Mus. Nov. 954: 17–19. 1937.

[9] SIMPSON, G. G., Amer. Mus. Nov. 817: 22–25. 1935.

hypocone in all the molars appears relatively heavy and more lingual in position than in *Ectocion*.

TABLE 3.—MEASUREMENTS (IN MILLIMETERS) OF UPPER TEETH, NO. 16691, OF PHENACODUS ALMIENSIS

Measurements	C	P^3	P^4	M^1	M^2	M^3
Anteroposterior diameter	5.8	8.2	8.5	9.0	9.2	7.8
Transverse diameter	4.0	7.3	8.5	10.0	11.0	10.6

The length of the preserved portion of the dentition, P^3 to M^3, is 42.5 mm. The length of the upper molars series, M^1 to M^3, inclusive, is 25.5 mm.

Ectocion sp.

A fragment of a left mandibular ramus exhibiting P_4 and the anterior part of the trigonid of M_1, U. S. N. M. no. 16695, is believed to represent a species of the condylarth *Ectocion*. The complete tooth appears to be about the size of P_4 in *E. ralstonensis*[10] from the Clark Fork beds. The cusps are relatively high and acute, and the pattern appears more crescentic in comparison with the inflated bunodont type of tooth seen in *Phenacodus*, although the entoconid is lacking as in that genus. However, *Ectocion ralstonensis* is described as having a relatively weak entoconid in comparison with the typical Gray Bull forms. A very slight cuspule is seen near the base of the protoconid posteriorly, as suggested in illustrations of P_4 belonging to the type of *E. ralstonensis*, not placed so high as observed in *Phenacodus* material. The hypoconid is more externally placed and both trigonid and talonid portions of the tooth have a much better developed crescentic pattern than in *Eohippus*. The enamel of the premolar is weakly rugose and there is a slight cingulum about the external wall.

The possibility of this specimen belonging to the form herein described as *Phenacodus almiensis* is not entirely eliminated, but the tooth is distinctly too small to occlude properly with the upper dentition of *P. almiensis*.

[10] See MATTHEW, W. D., and WALTER GRANGER, *ibid.*, p. 353. 1915.

Obituary

THOMAS HERBERT NORTON, distinguished author, diplomat, and research chemist, died on December 2, 1941, after a short illness.

Dr. Norton was born June 30, 1851, at Rushford, N. Y. He was graduated from Hamilton College in 1873 as valedictorian. In 1883, after many colorful experiences abroad, which were vividly described by Charles E. Monroe in the "News Edition" of the American Chemical Society for August 10, 1935, he became professor of chemistry at the University of Cincinnati. In 1900, he was appointed American consul at Harput, Turkey; in 1905 he was transferred to Smyrna, and in 1906 he went to Chemnitz, Germany. Beginning in 1911, Dr. Norton made a survey of the chemical industries of foreign countries for the Department of Commerce. When he returned to the United States he was chosen for the preparation of a report on the supply of dyestuffs for American industries. The report that he prepared revealed that foreign firms not only manufactured the chief part of the dyestuffs used in the United States, but that they employed various means to prevent the entrance of American rivals into the field of competition. Dr. Norton took a most active part in securing legislation to alleviate these unsatisfactory conditions and to foster the American chemical industry.

Dr. Norton's outstanding ability and wide interest brought him many honors and responsibilities. He received honorary degrees from Hamilton College and from the University of Heidelberg; in 1937 he received the Lavoisier Medal. Among the many scientific organizations to which he belonged was the Washington Academy of Sciences.—H.S.I.